Deep Virtual Production of Pion Pairs

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Project

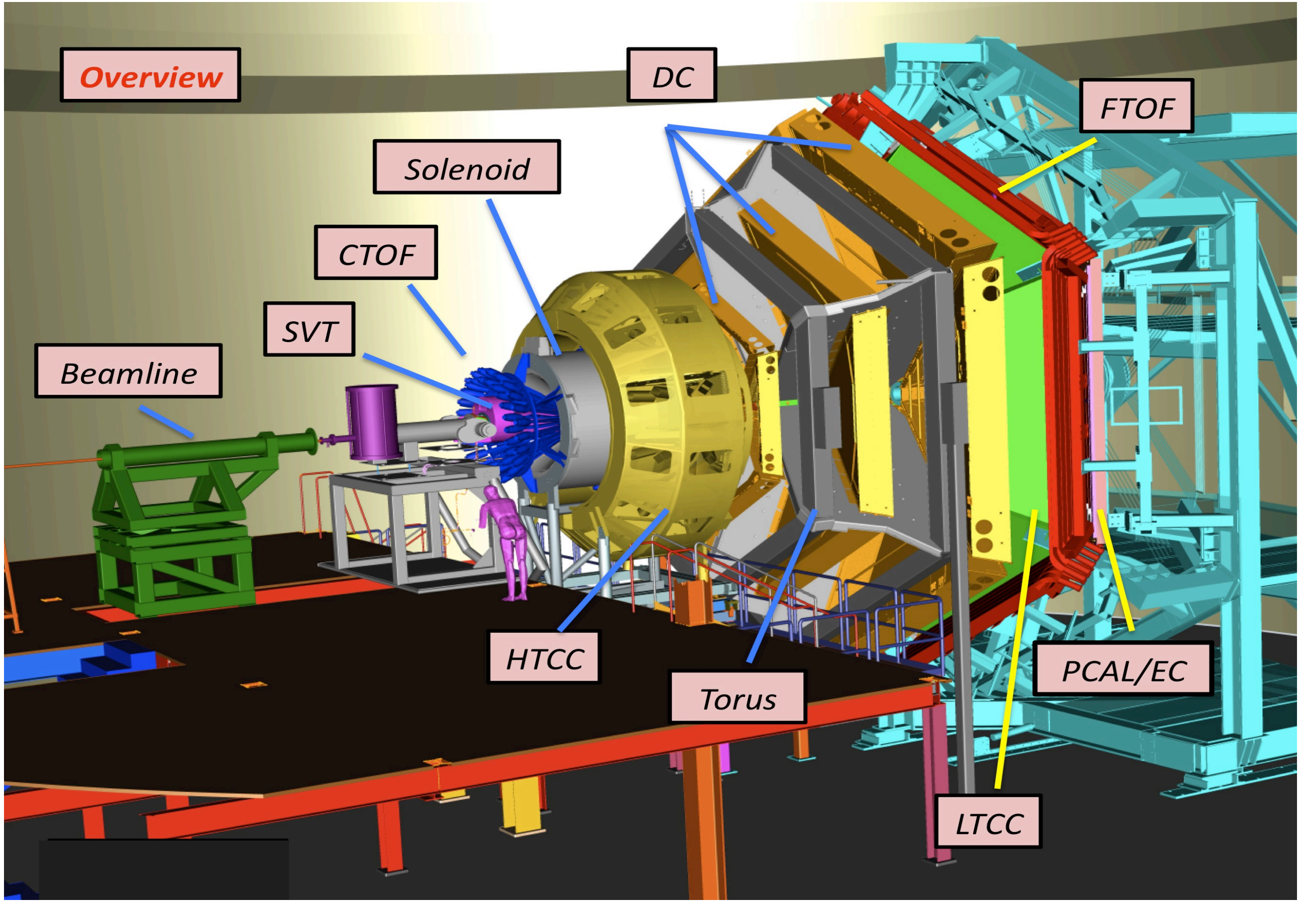
- We are mainly considering two reactions, Charged and Neutral Pion Pairs
  - $ep \rightarrow e'p'\pi^+\pi^-$
    - Isospin I=1, angular momentum J=1
      - $\rho(770)$
    - Isospin I=0, angular momentum J=0
      - $f_0(500) = \sigma, f_0(980)$
  - $ep \rightarrow e'p'\pi^0\pi^0$
    - Isospin zero, spin zero channel (I:J=0:0)
      - $f_0(500) = \sigma, \quad f_0(980)$

CLAS12 Equipment in Hall B

Forward Detector (FD)
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter
- Forward Tagger
- RICH detector

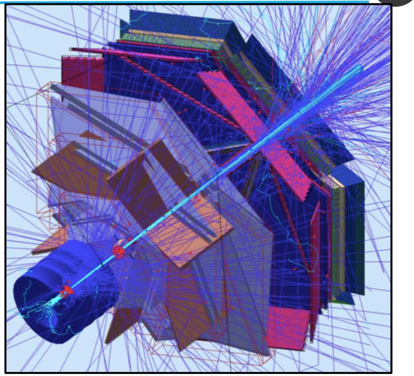
Central Detector (CD)
- Solenoid magnet
- Silicon Vertex Tracker
- Central Time-of-Flight
- Central Neutron Det.
- MicroMegas

Beamline
- Photon Tagger
- Shielding
- Polarized Targets



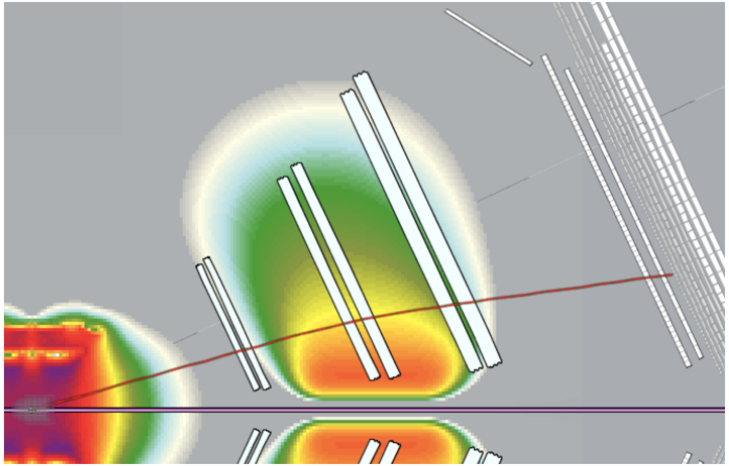
CLAS12 Simulation and Reconstruction

- **GEMC – GEant4 Monte Carlo**
  - The official detector simulation of CLAS12
  - Developed by Maurizio Ungaro
  - For more information gemc.jlab.org.



- **Coatjava – CLAS Offline Analysis Tools**
  - Offline common tools for building CLAS12 reconstruction, calibration, and analysis software
  - developed by Gagik Gavalian
  - For more information

https://claraweb.jlab.org/clara/docs/clas/installation.html



RG-A Analysis

Data : /work/clas12/rg-a/trains/v2/skim8_ep

skim8_5038.hipo
skim8_5117.hipo
skim8_5046.hipo
skim8_5001.hipo
skim8_5030.hipo
skim8_5000.hipo
skim8_5036.hipo

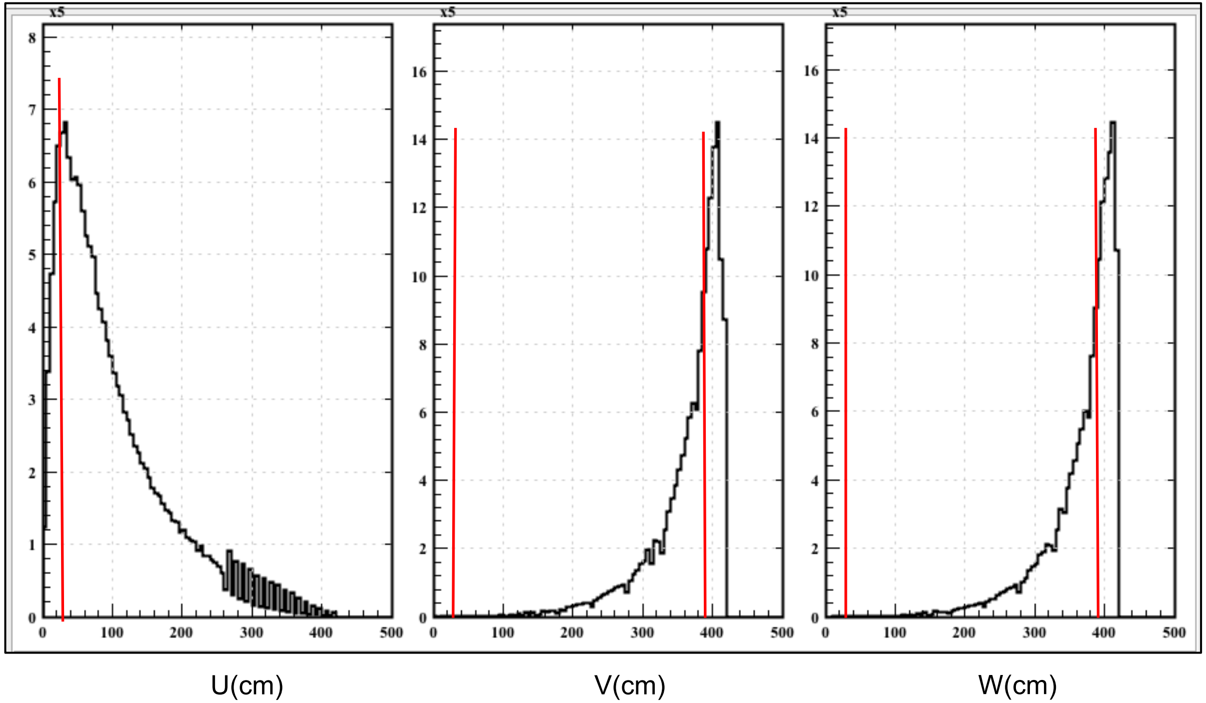
Coatjava version 5b.7.8

- Identify Electrons
  - Fiducial cuts in PCAL + Tracking
  - ECAL & HTCC cuts
- Identify Protons
  - Tracking fiducial
  - TOF
- Identify pions

(Compare with Event Builder for sanity check)

RG-A Analysis: PCAL Fiducial

U , V and W for PCAL



- PCAL U, V, W cuts

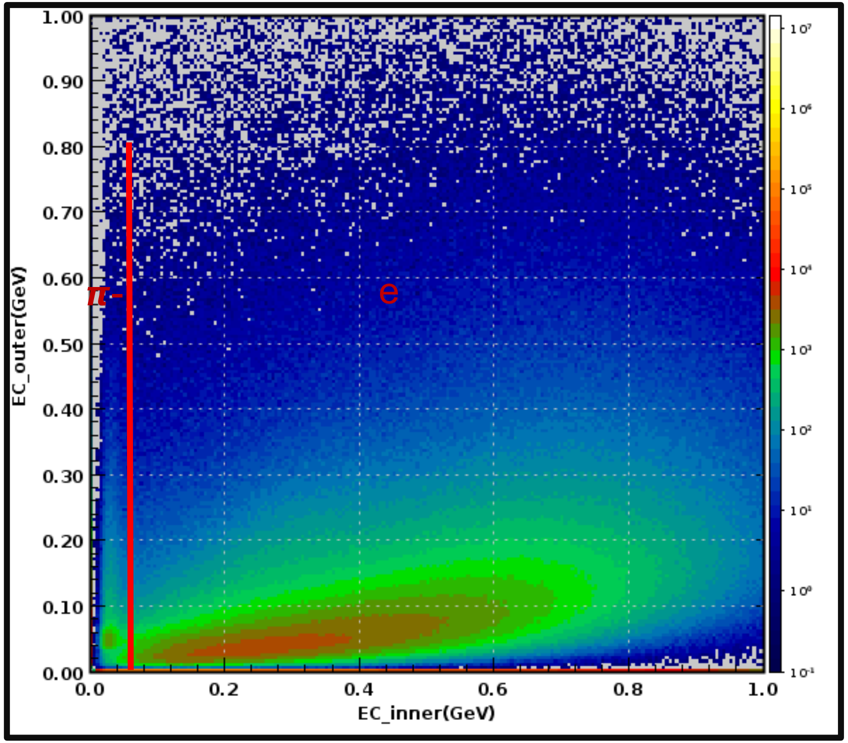
U > 30 , 30 < V <390, 30 < W <390

- EM shower is broad ; Remove events close to edges, as shower leaks out and sampling fraction not reliable for electron id

RG-A Analysis

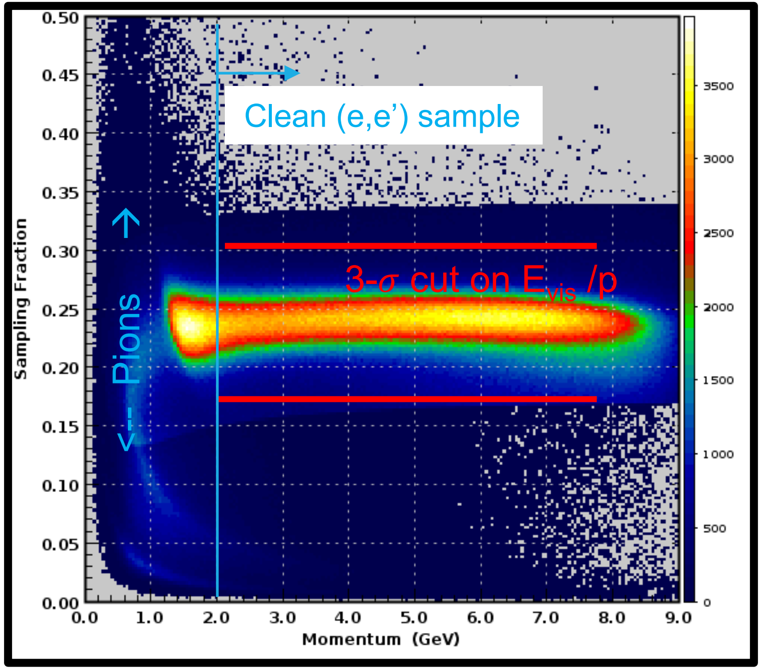
Calorimeter:

- High energy pions give a constant signal (Minimum ionizing)
- Electrons shower and stop: Sampling fraction = visible “energy” / momentum(from tracking)

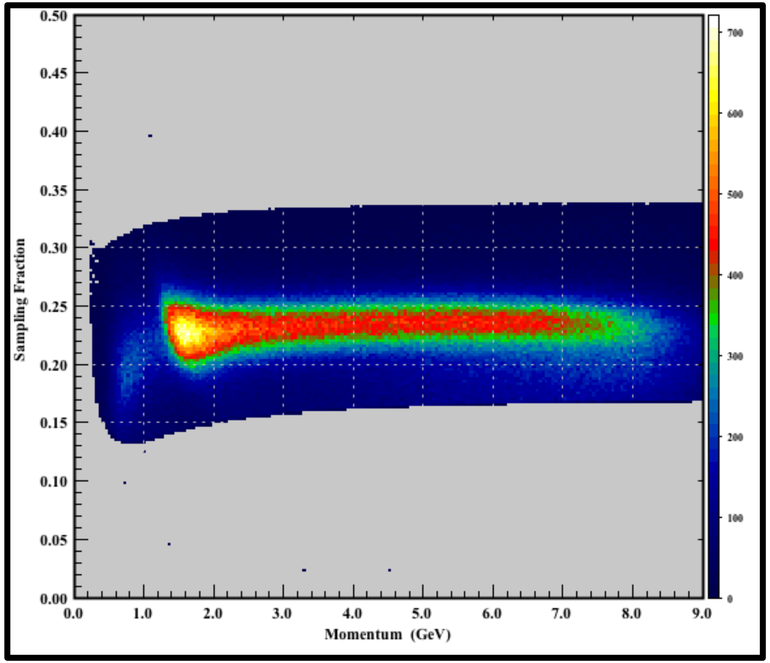


RG-A Analysis

For all negative particles



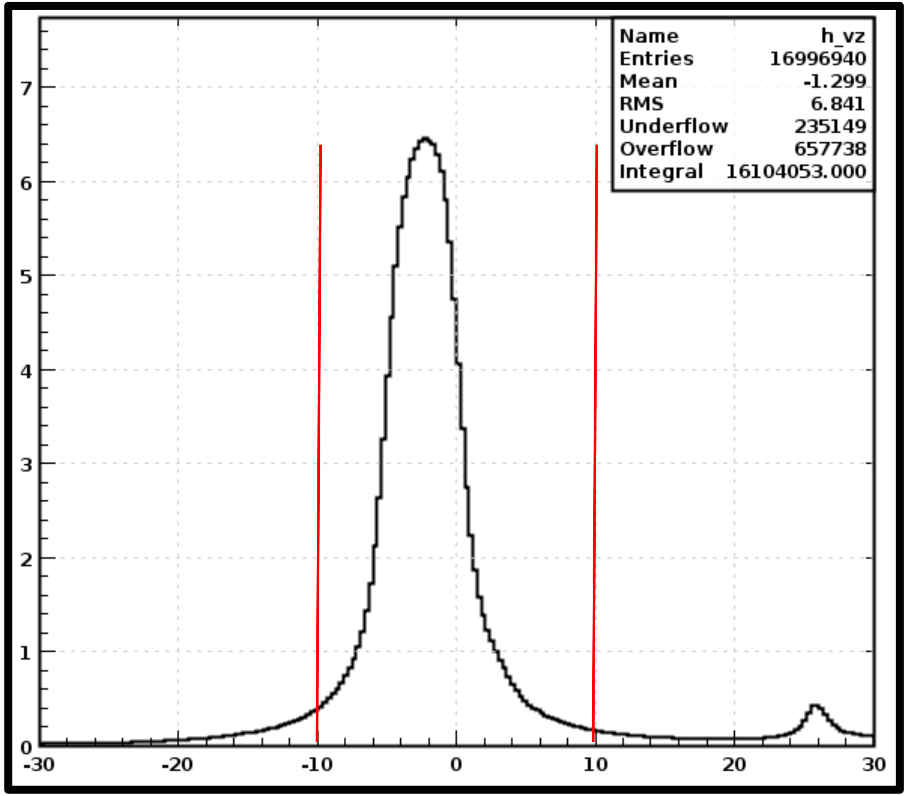
Just for Particle#0



E/p vs p plots of just particle #0

RG-A Analysis: Target Vertex

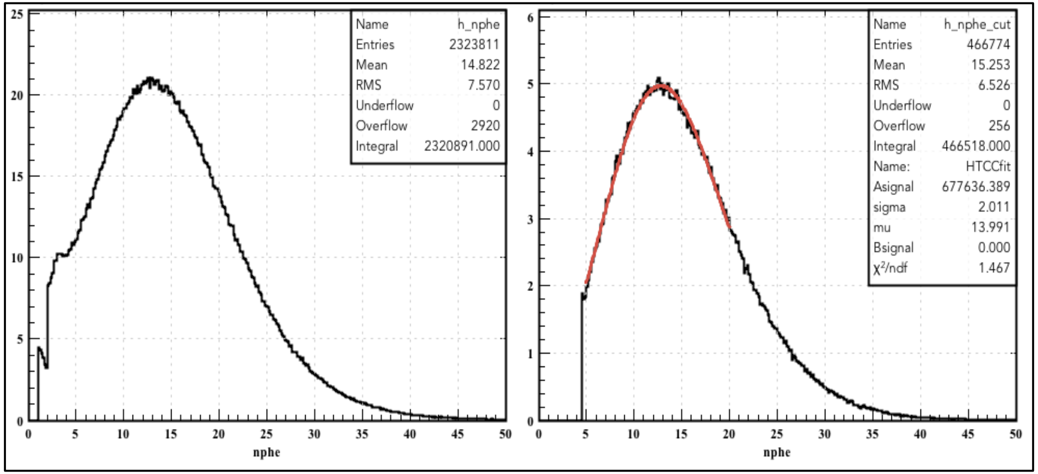
V_z distribution



vz(cm)

RG-A Analysis

HTCC number of photo electrons (all negative particles)



Before applying any cuts

After applying cuts

Cuts

- PCAL U, V, W cuts

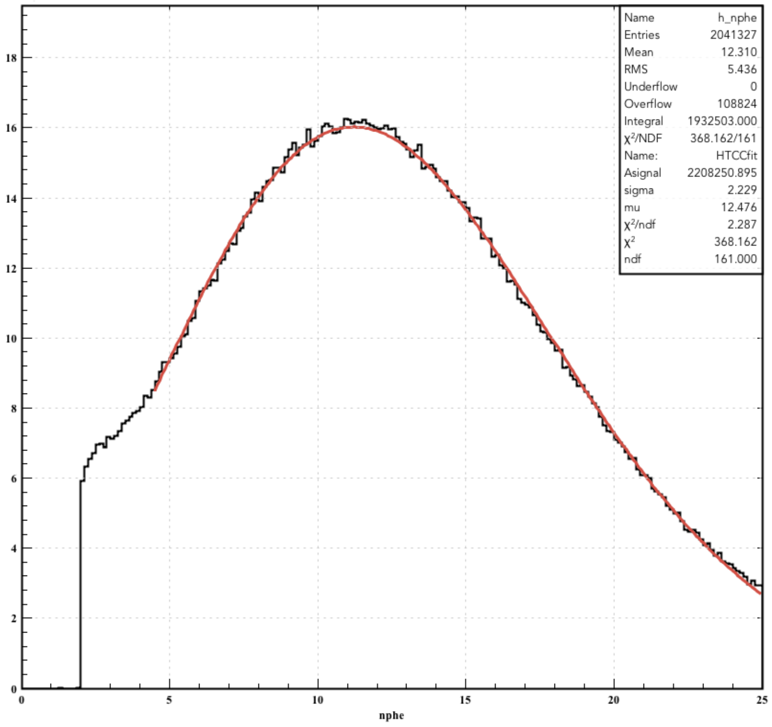
U > 30 , 30 < V <390, 30 < W <390

- Energy_ECinner > 60 MeV
- 0.18 < ECAL_energy/p < 0.30
- -10.0 cm < V_Z < 10.0 cm
- P > 2.0 GeV
- Nphe > 4.5

Fit function= Poisson ⊗ Gauss_error
Mean of 14 photo-electrons per electron track
(id from ECAL)

RG-A Analysis

HTCC number of photo electrons for just particle#0

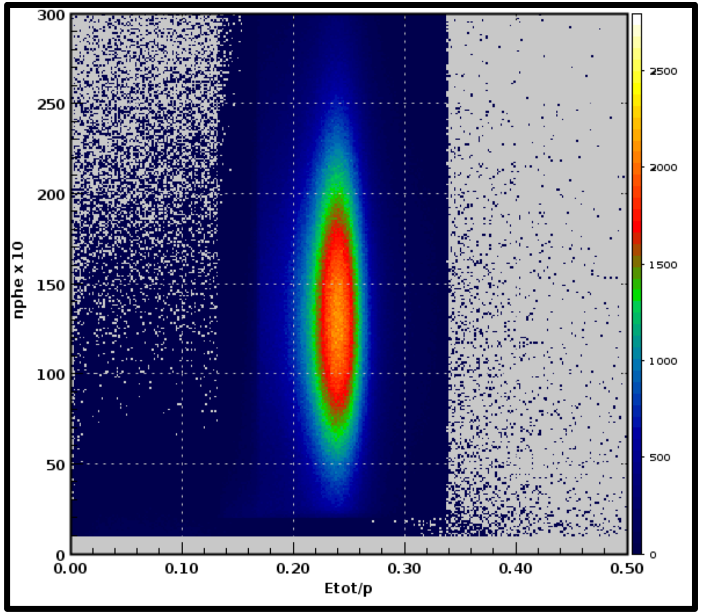


skim8_4013.hipo

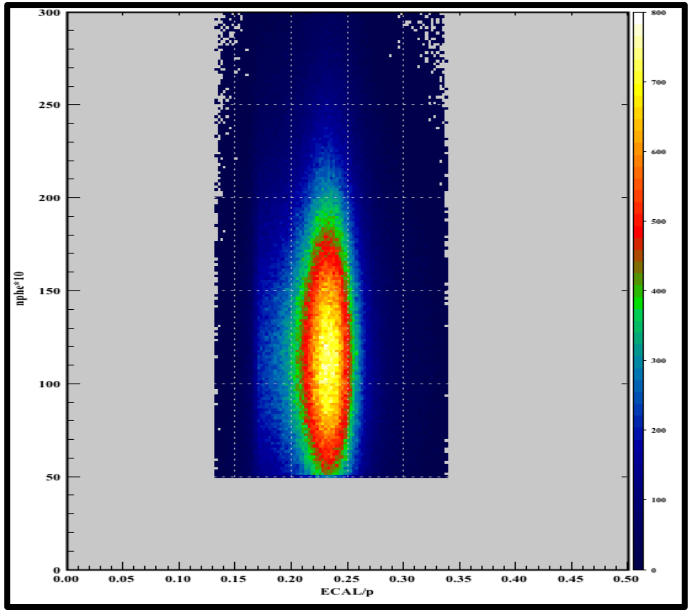
Fit function= Poisson ⊗ Gauss_error

RG-A Analysis

Nphe*10 vs Etot/p for all negative particles



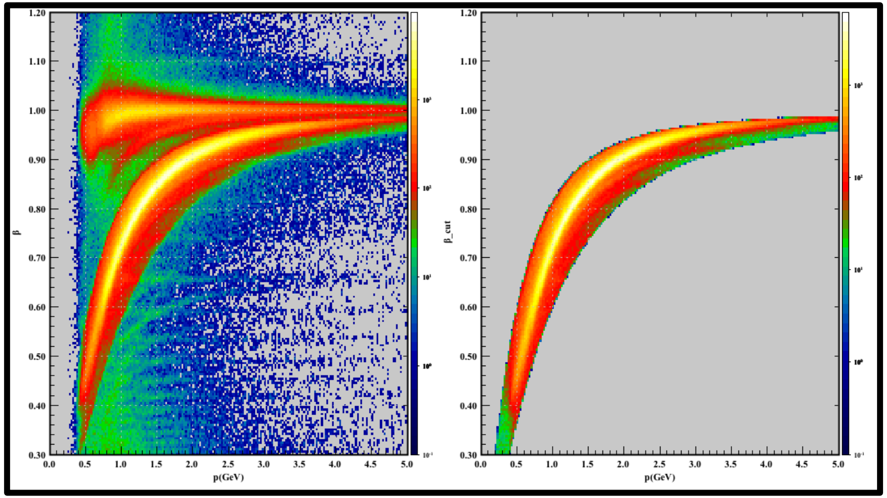
Nphe*10 vs Etot/p for just particle#0



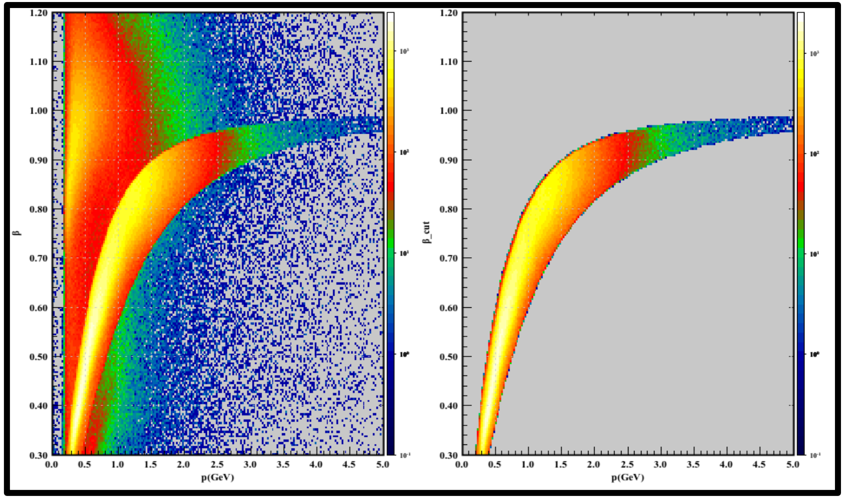
RG-A Analysis: TOF vs momentum

Identifying Protons

β =(d/tof•c) vs p for FTOF



Beta vs p for CTOF



Pions,
Kaons,
Protons
accidentals

Cut →

$\beta_1(p) < \beta(p) < \beta_2(p)$

$\beta_2(p) = (1/2)(\beta\,(kaon)(p) + \beta(proton)(p))$

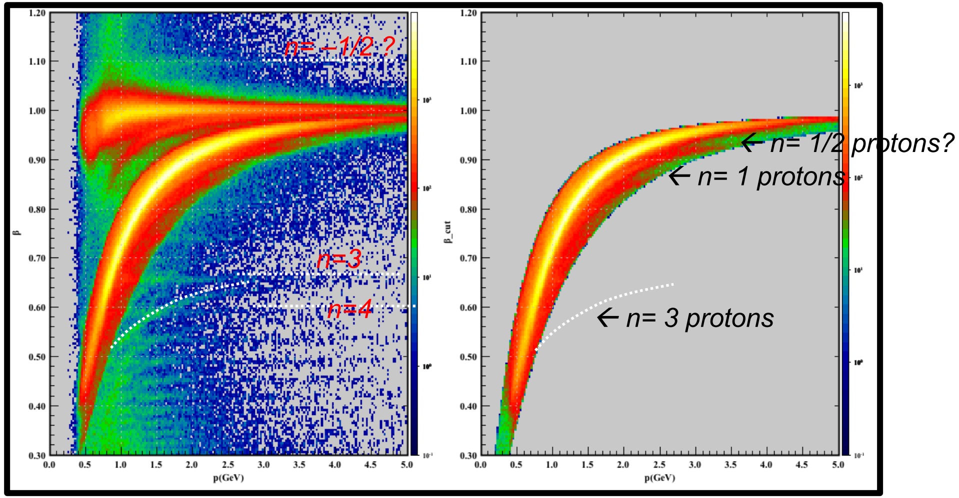
$\beta_1(p) = (1/2)(\beta\,(proton)(p) + \beta(deuteron)(p))$

$$\beta(kaon)(p) = \frac{p}{\sqrt{p^2 + m_K^2}}$$

Similar for protons, deuterons,…

RG-A Analysis: Accidentals

Beam bunches separated by 4 ns.
All timing based on highest energy electron in event
Time of Flight = tof = $(t - t_e)_{FTOF}$

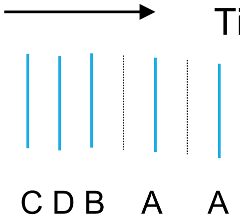


Accidental pions and protons visible

β =(d/tof•c) in FTOF

- Some particles came from target at time offset nΔt = ±4ns, ±8ns…
- β_n = (d/c) / (tof+nΔt), d_{FTOF}~7m
- Relativistic particles
  tof to FTOF ~ 23.3 ns
  Accidentals: 4ns/tof = 0.17
  β_n = *1/(1 + n•0.15)*
- Bleed-through (Halls A & C) at half integer values?

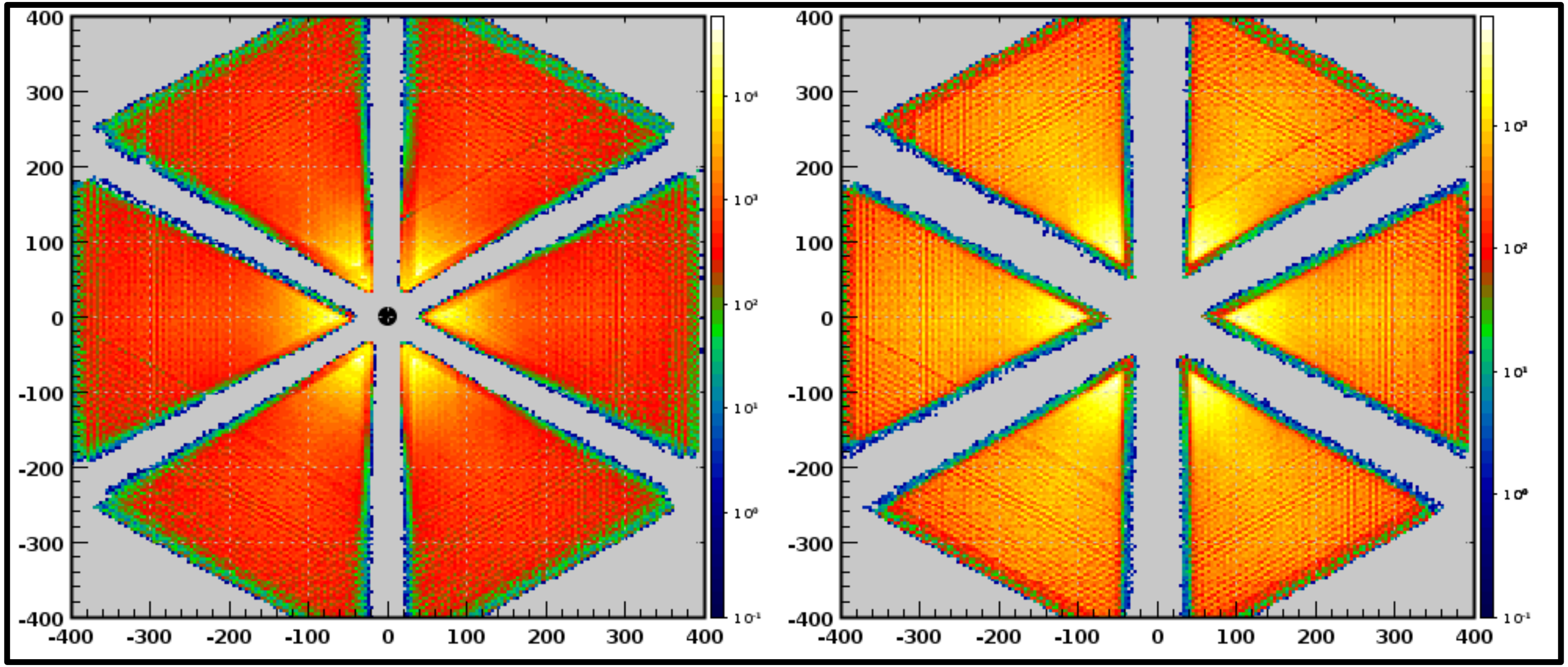
Time in 0.667 ns steps



RG-A Analysis

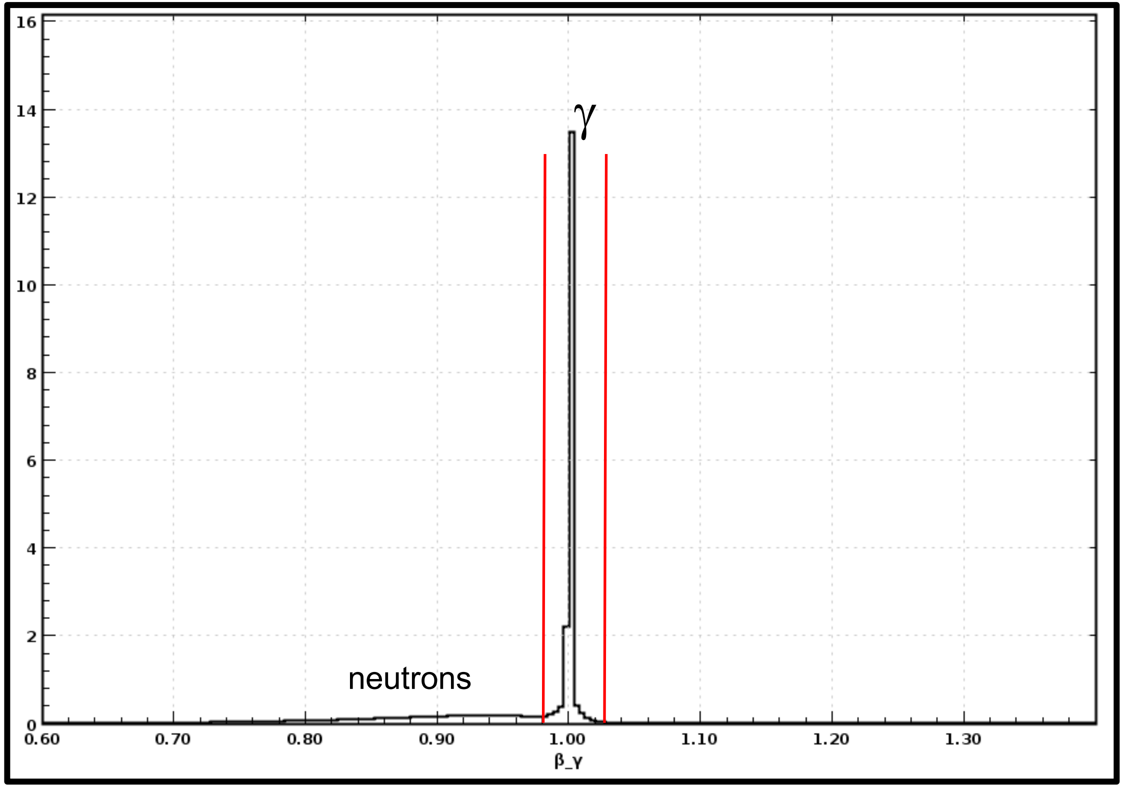
Identifying Photons

ECAL Y vs X plot for neutral particles before and after applying PCAL
U > 30 , 30< V < 390 , 30 < W <390



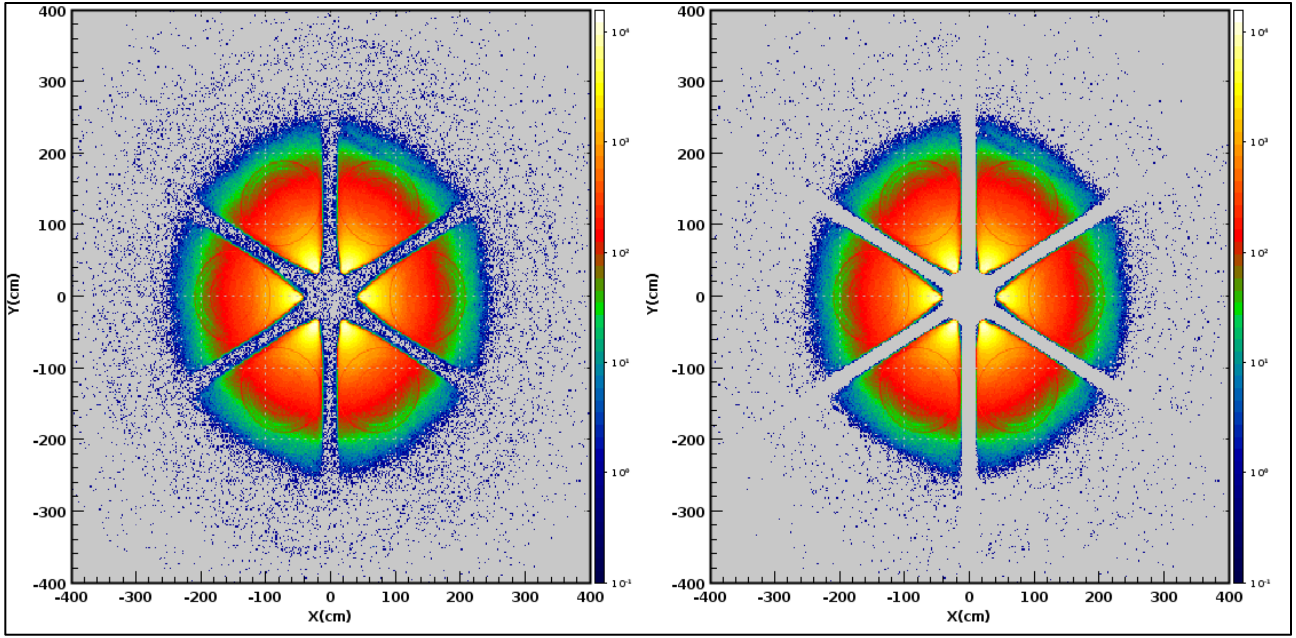
RG-A Analysis

Identifying Photons



RG-A Analysis

DC Fiducial Cut (Region2)



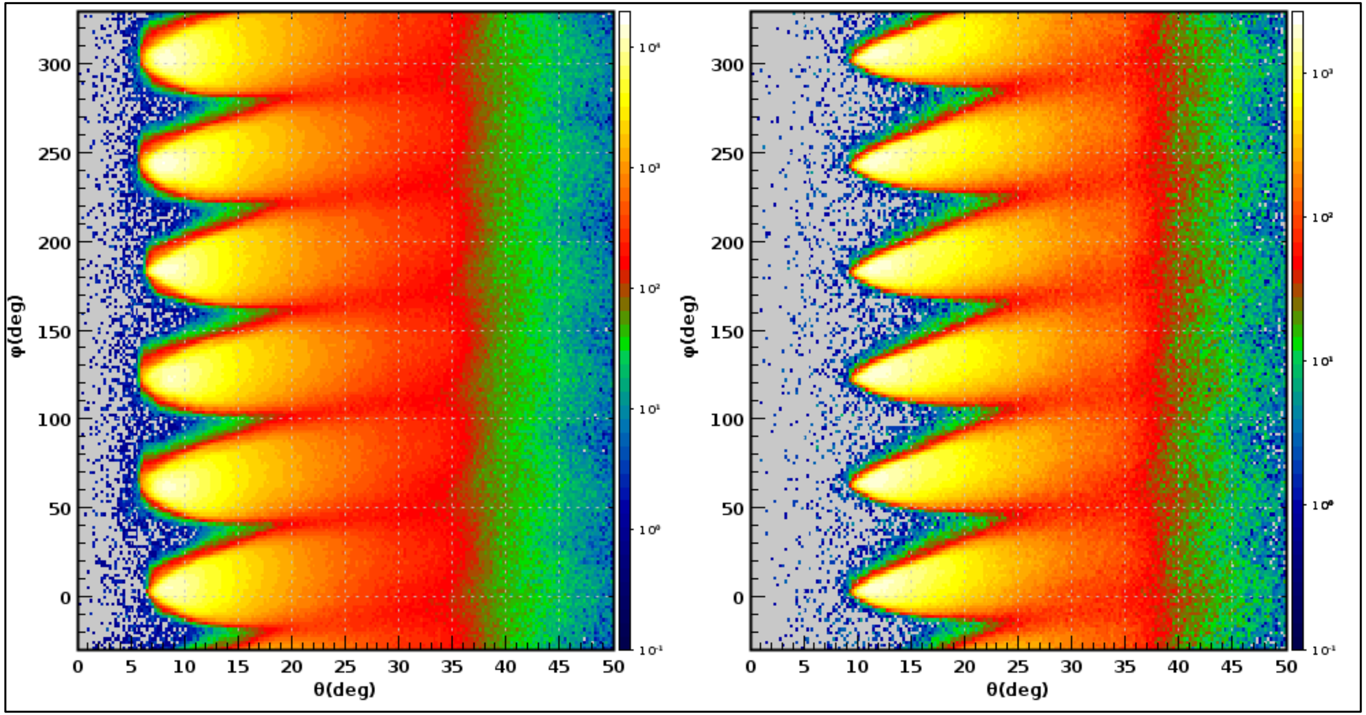
$rth = (S-1)\frac{\pi}{3};$
$XS = \cos(rth)\,X + \sin(rth)\,Y\,;$
$YS = -\sin(rth)\,X + \cos(rth)\,Y\,;$
$\phi_S = \text{atan2}(YS, XS - r\_cut/2);$

$(XS * XS + YS * YS > r\_cut * r\_cut)$ and $|\Phi_S| < \frac{\pi}{3}$

RG-A Analysis

ECAL Φ vs θ distribution for negative particles

PCAL U > 30 , 30< V < 390 , 30 <W <390
PCAL_Doca< 3.0
DC_fiducial cut



before after

Notice tilt due to solenoid field

RG-A Analysis

- My acceptances are not really good. (Because we didn't finish it yet.)

- Back to event builder pid
- For now on, Used following cuts for every plots

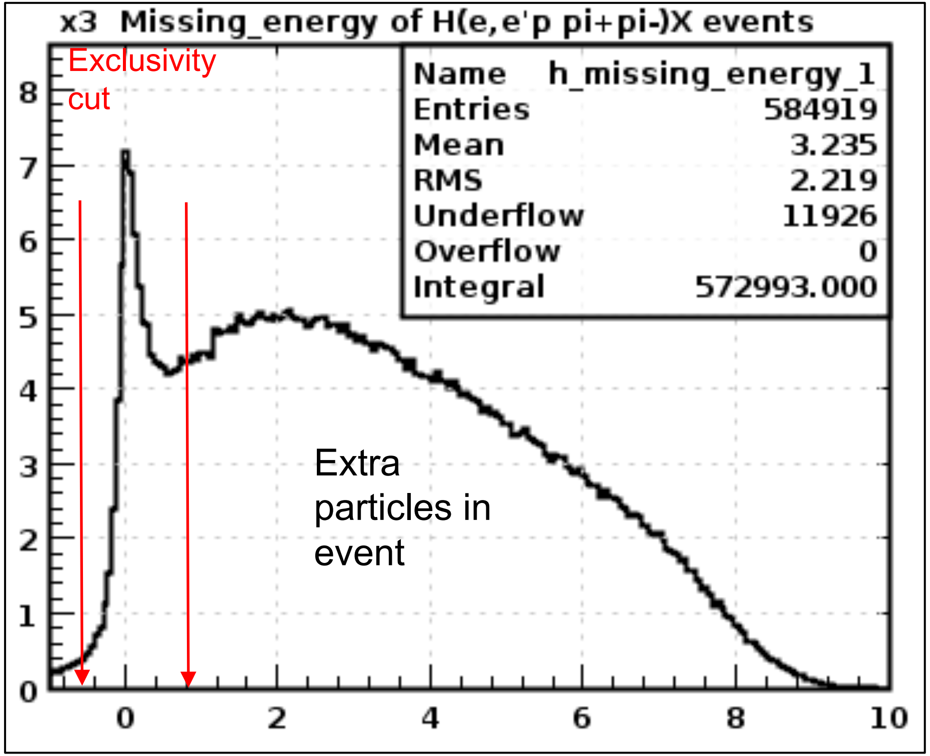
electron – PCAL cuts (U > 30 , 30< V < 390 , 30 <W <390)
Region 2 DC fiducial cuts

Proton, π^+ π^- - Region 2 DC fiducial cuts

Photon - PCAL cuts (U > 30 , 30< V < 390 , 30 <W <390)

RG-A Analysis

Missing energy distribution for events with $H(e, e'p\pi^+\pi^-)X$



RG-A Analysis

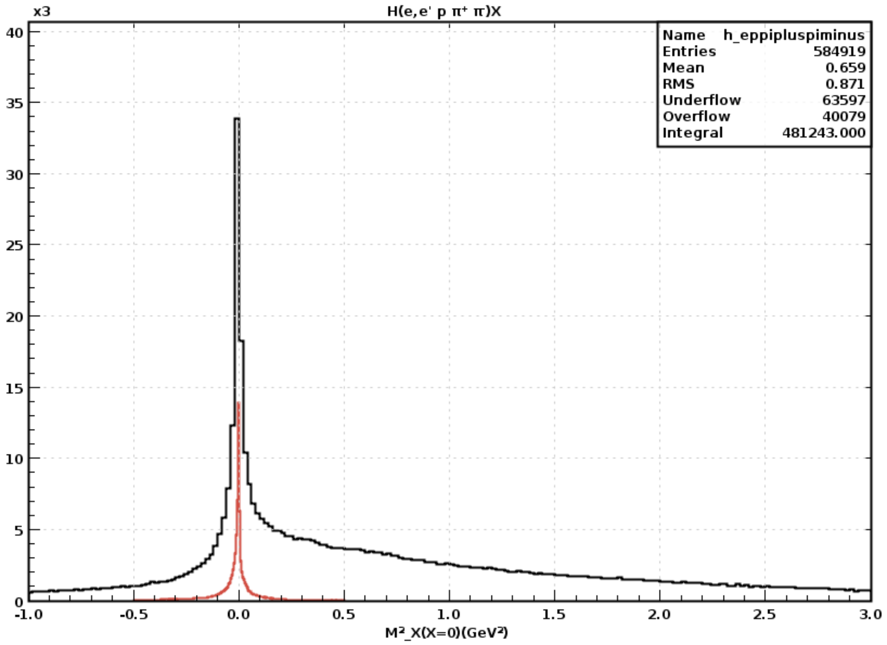
Missing mass distribution X

Missing Energy $H(e,e'p\,\pi^+\pi^-)X > -0.5$ and $H(e,e'p\,\pi^+\pi^-)X < 0.8$ cut

Before Cut

After Cut

$H(e,e'p\,\pi^+\pi^-)X$



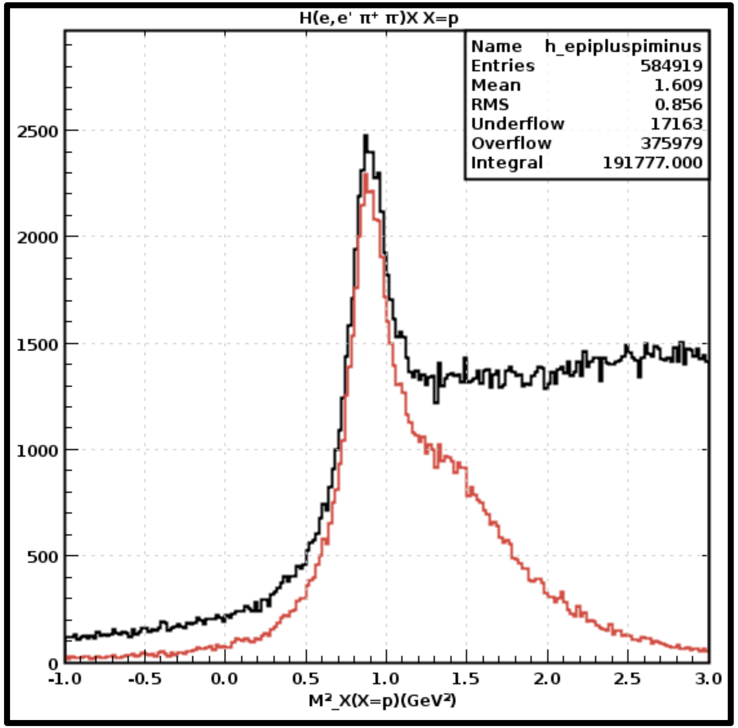
RG-A Analysis

Missing mass square distribution for proton

Missing Energy $H(e,e'p\pi^+\pi^-)X > -0.5$ and $H(e,e'p\pi^+\pi^-)X < 0.8$ cut

—	Before Cut
—	After Cut

$$H(e,e'\pi^+\pi^-)X \ (X=p)$$

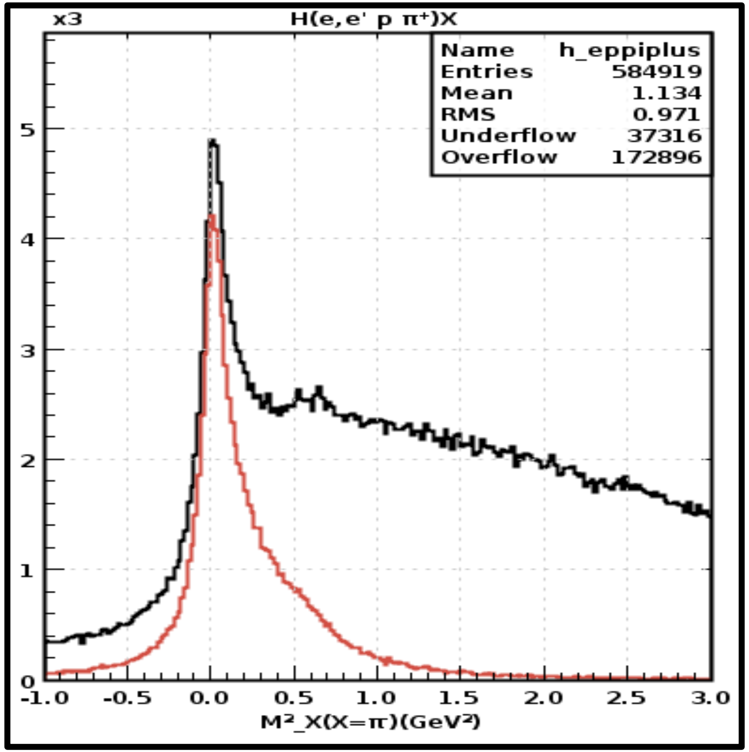


RG-A Analysis

Missing mass of π^- distribution after applying

Missing Energy $H(e, e'p\pi^+\pi^-)X > -0.5$ and $H(e, e'p\pi^+\pi^-)X < 0.8$ cut

$H(e, e'p\pi^+\pi^-)X \quad (X = \pi^-)$



Before Cut

After Cut

RG-A Analysis

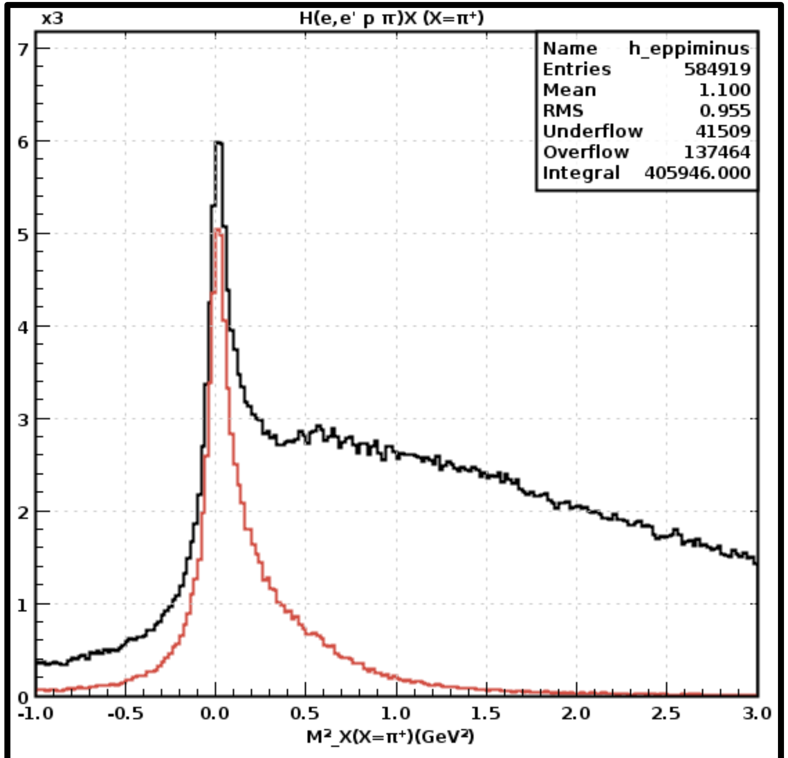
Missing mass distribution after applying

Missing Energy $H(e, e'p\pi^+\pi^-)X > -0.5$ and $H(e, e'p\pi^+\pi^-)X < 0.8$ cut

Before Cut

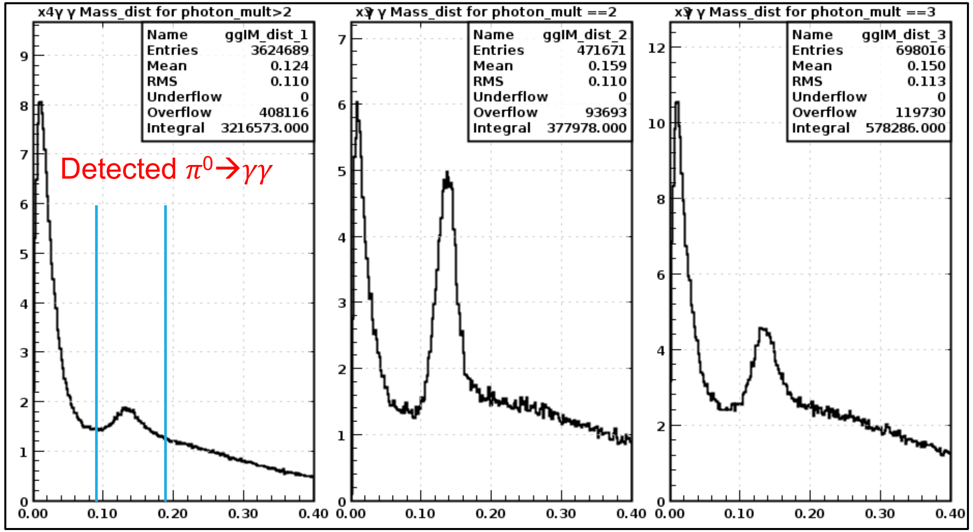
After Cut

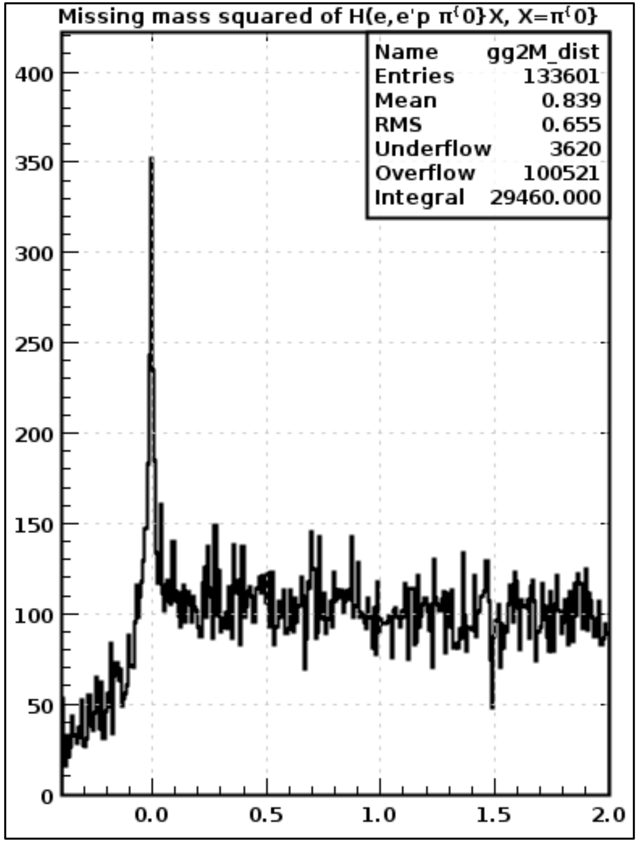
$H(e, e'p\pi^+\pi^-)X \quad (X = \pi^+)$



RG-A Analysis

$ep \rightarrow e'p'\pi^0\pi^0$





The peak at 0 is probably mostly missing Bremstrahlung photons

Simulation of Deep Virtual Production of Pion Pairs

Event Generation

- Monte-Carlo Generation of Phase Space Variables
  - There are eight independent kinematic variables in the final state of the $ep \rightarrow e'p'\pi\pi$ reaction.

Total kinematic variables in final state (four 4-vectors)	16
Mass constraint of the four final state particles	-4
Four-Momentum Conservation, initial to final state	-4
Total number of independent variables in final state	8

- These are,
  - Q^2 , xB , ϕ_e, $M^2_{1,2}$, t, $\phi^*_{1,2}$, $\cos\theta_{\pi 1 \text{ in } \pi\pi \text{ rest}}$, $\phi_{\pi 1 \text{ in } \pi\pi \text{ rest}}$

Simulation and Reconstruction

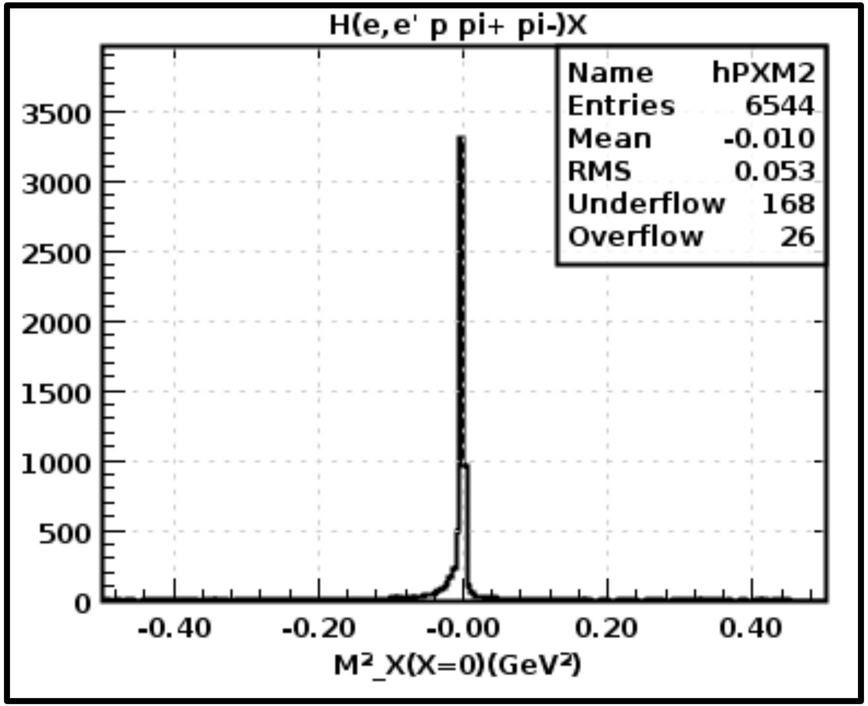
- For my simulation and reconstruction, I used
  GEMC version 4.3.0
  COATJAVA version 5b.7.8

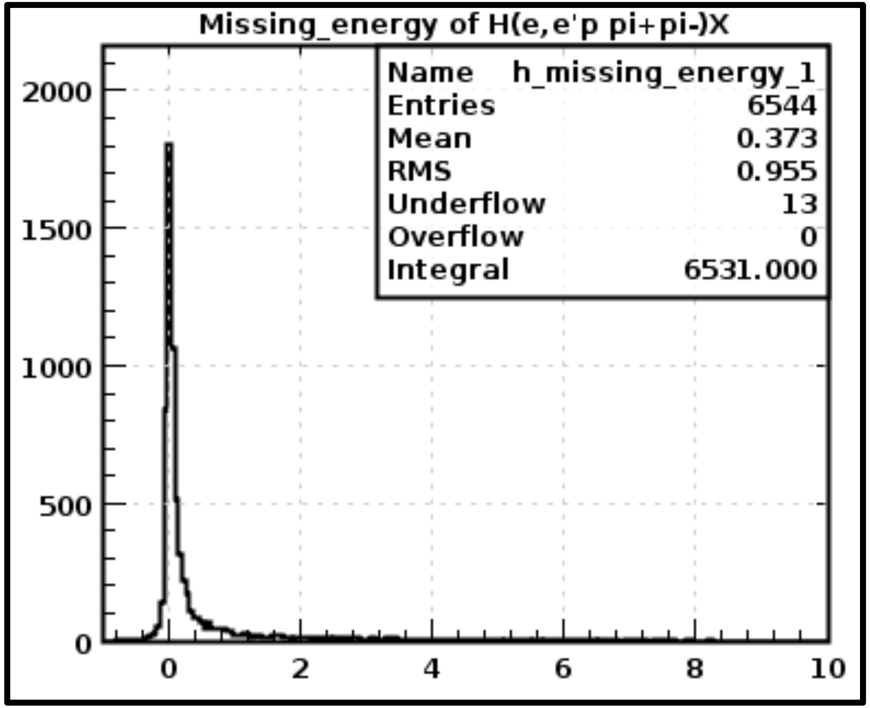
Steps :

- After generation monte carlo data is passed through the GEMC in the form of LUND format (for 100k events).
- Reconstruction is done with coatjava.
- CLAS12 analyses are done with java.
- This method ties well with the coatjava framework and provides standard tools for reading EVIO files and reconstructed banks.

Missing mass and Missing Energy for $ep \rightarrow e\ p\ \pi^+\ \pi^-\ X$

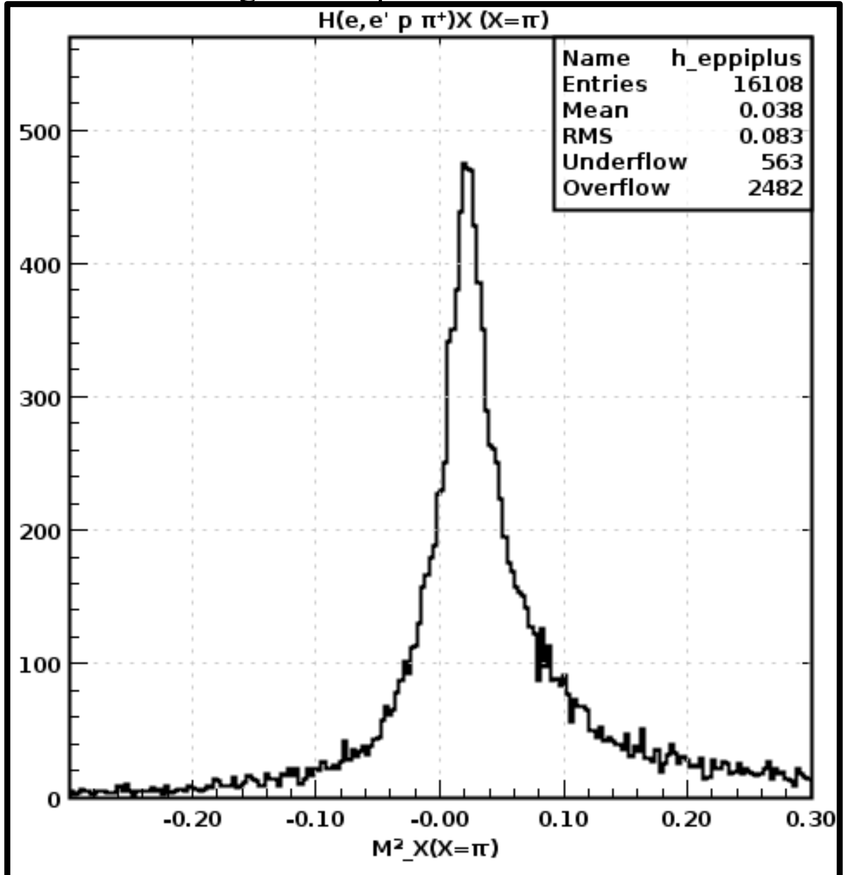
Simulation of $ep \rightarrow ep\pi^+\pi^-$ events





Missing mass for ep → e p π⁺ X

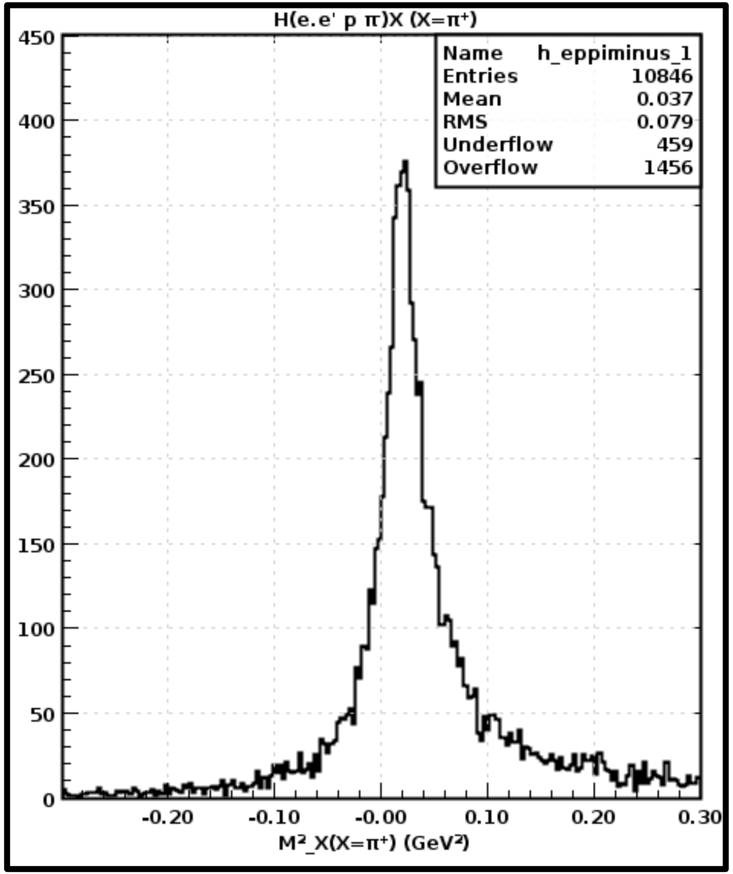
- Reconstruction of π^- from Missing mass squared
- π^- not detected



Simulation of $ep \rightarrow ep\pi^+\pi^-$ events

Missing mass for ep → e p π⁻ X

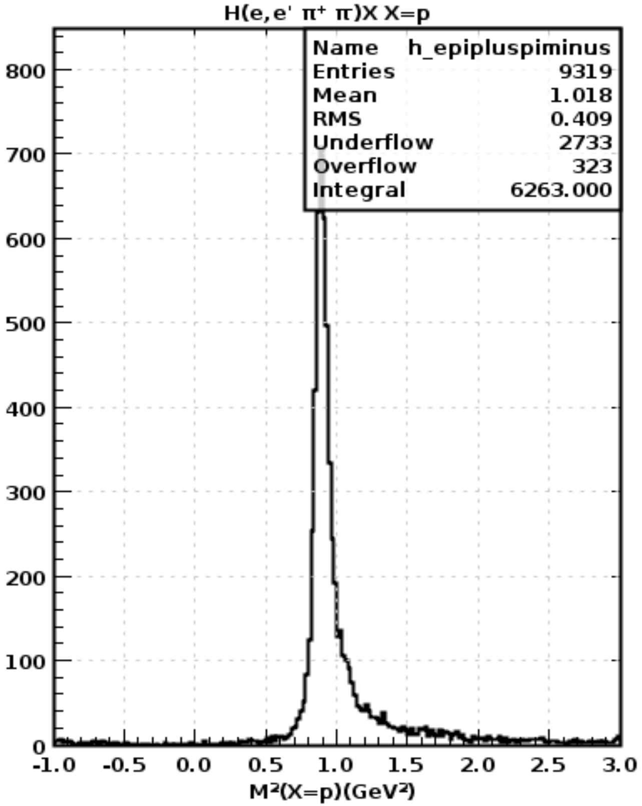
- Reconstruction of π^+ from Missing mass squared
- π^+ not detected



Simulation of $ep \rightarrow ep\pi^+\pi^-$ events

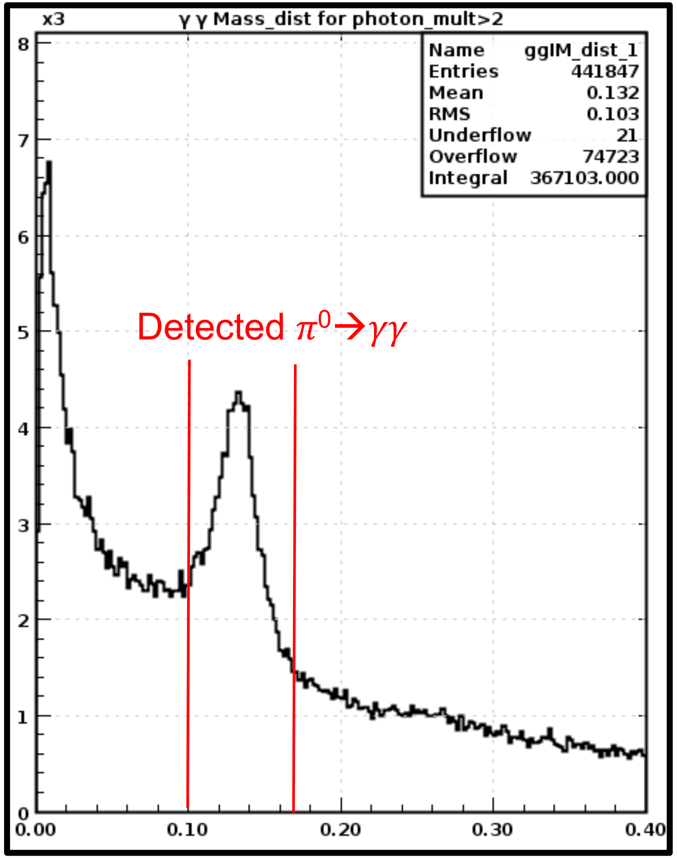
Missing mass for $ep \rightarrow e\ \pi^{+}\ \pi^{-}\ X$

- Reconstruction of proton from missing mass squared
- Proton not detected

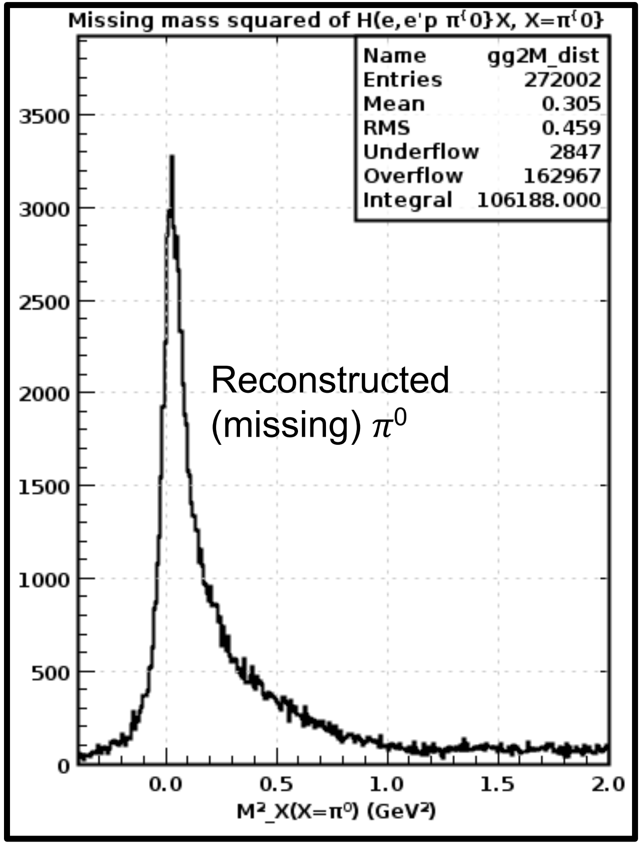


Simulation of $ep \rightarrow ep\pi^{+}\pi^{-}$ events

Missing mass for $ep \to e'p'\pi^0X$



Simulation of $ep \to ep\pi^0\pi^0$ events



- Applied a cut on invariant mass : around $0.10 < m_{\gamma\gamma}^2 < 0.17\ GeV$

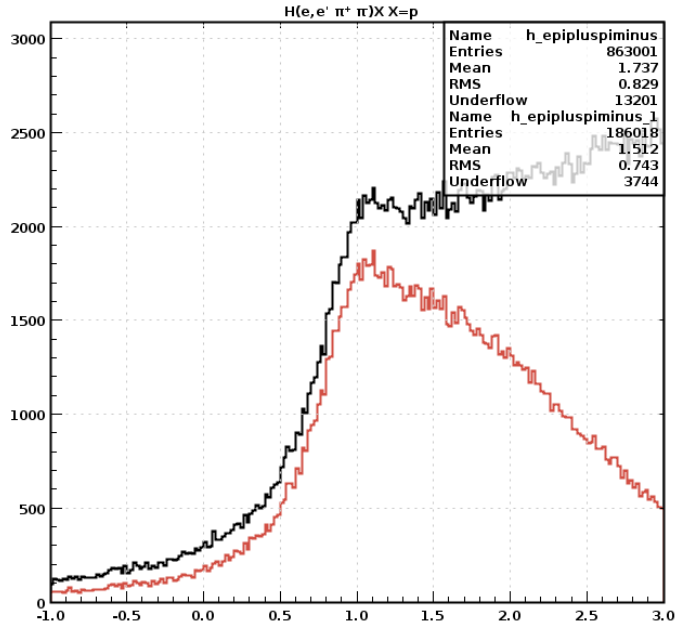
Thank You

RG-A Analysis

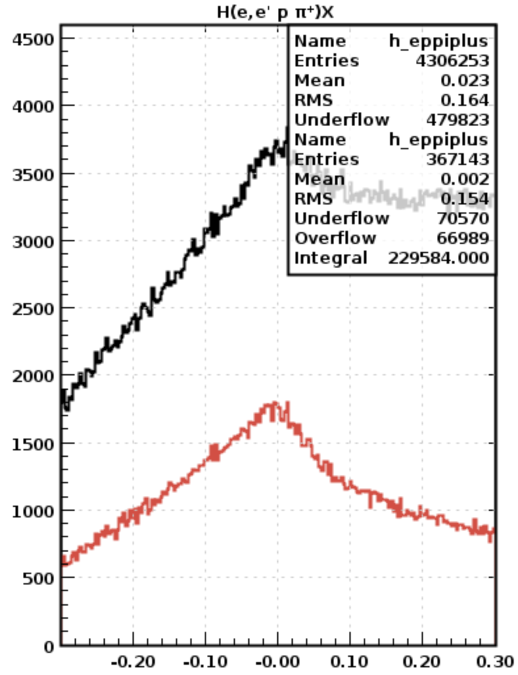
$H(e,e'\pi^{+}\pi^{-}p)$ events

Sample reconstruction of one missing particle, before/after missing energy cut

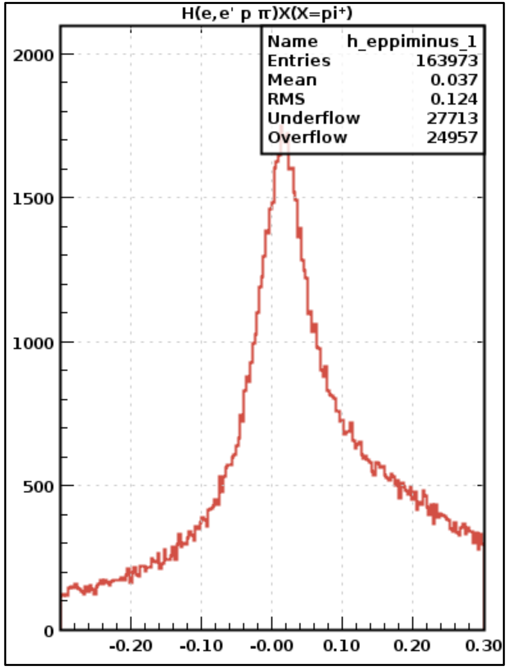
$H(e,e'\pi\,\pi^{-}p)$ X



M^2_X(X=p)(GeV^2)



M^2_X(X=pi-)(GeV^2)

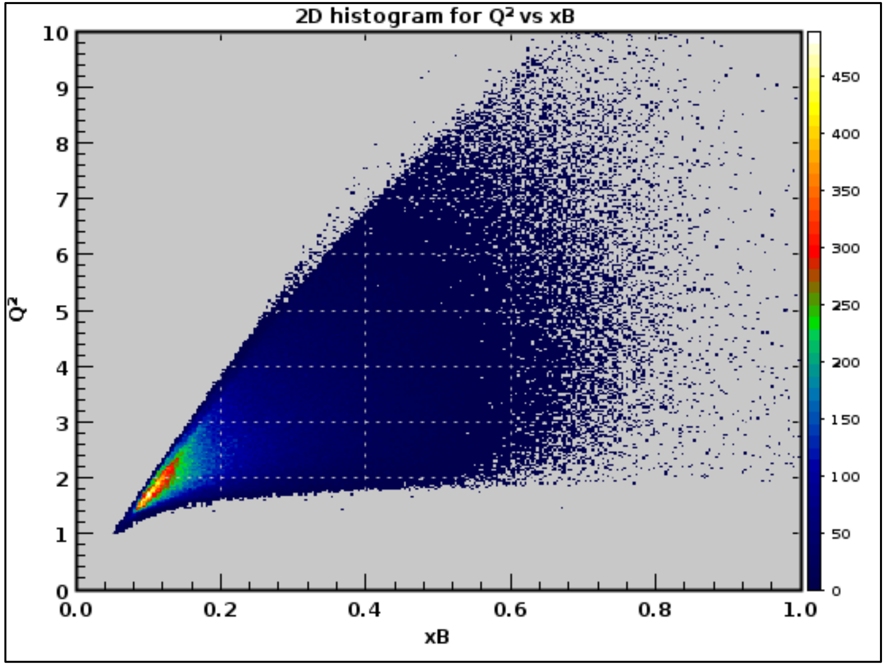


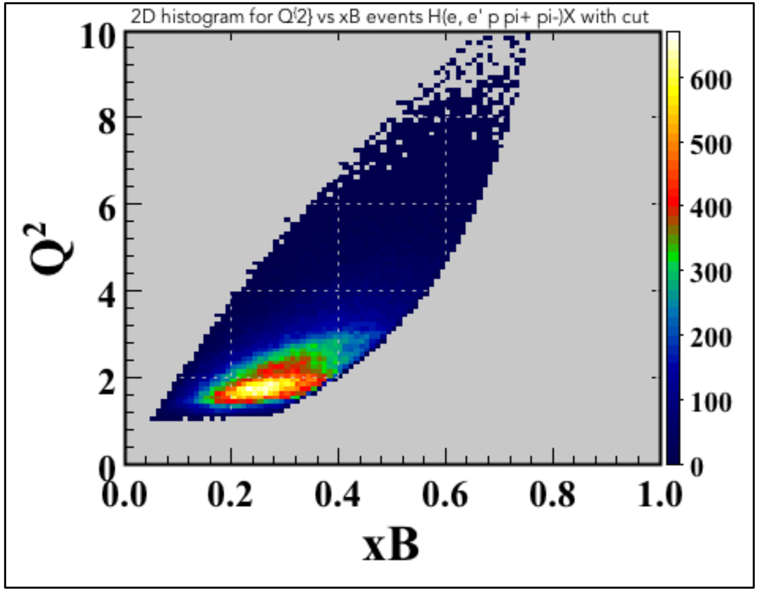
M^2_X(X=pi+)(GeV^2)

RG-A Analysis

Back up slides

RG-A Analysis



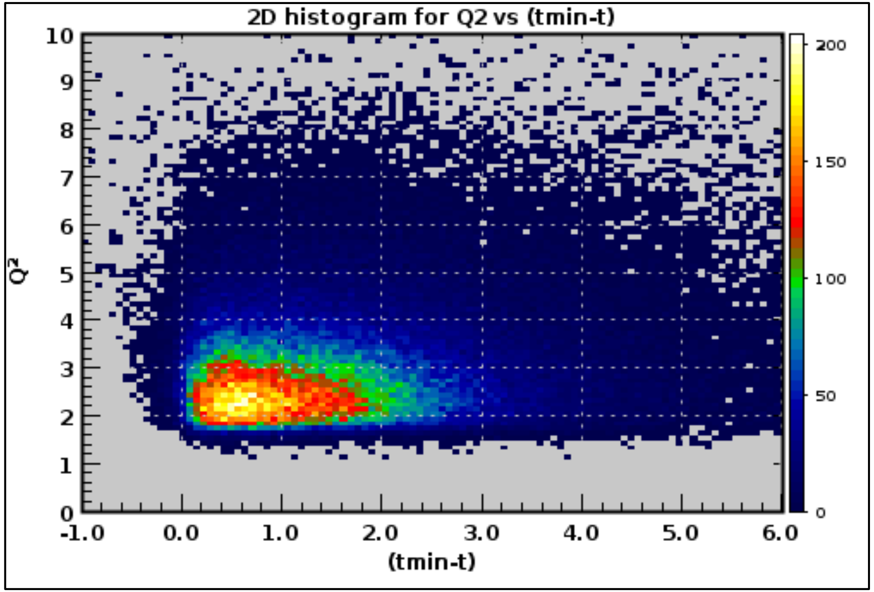


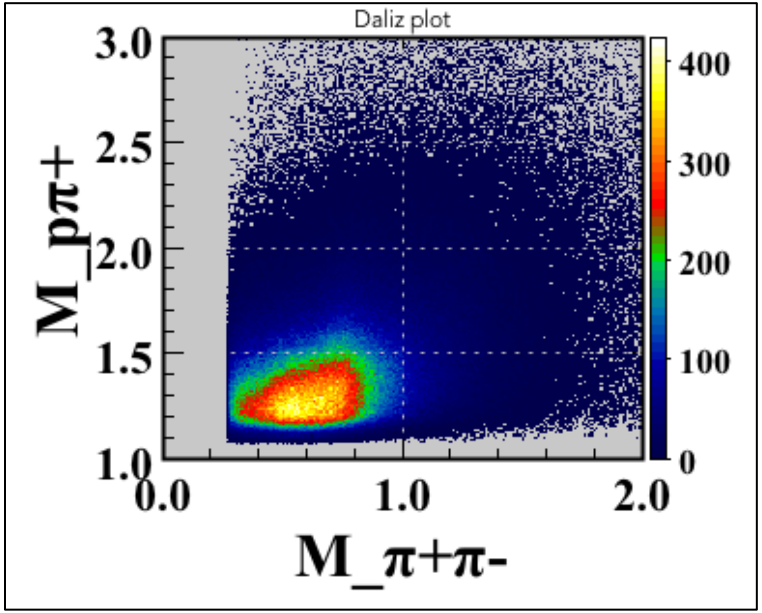
Applied Cuts: $Q^2 > 1.0\ GeV^2$ and $W^2 > 4\ GeV^2$

Missing Energy $H(e, e'p\,\pi^+\pi^-)X > -0.5$ and $H(e, e'p\,\pi^+\pi^-)X < 1.5$

RG-A Analysis

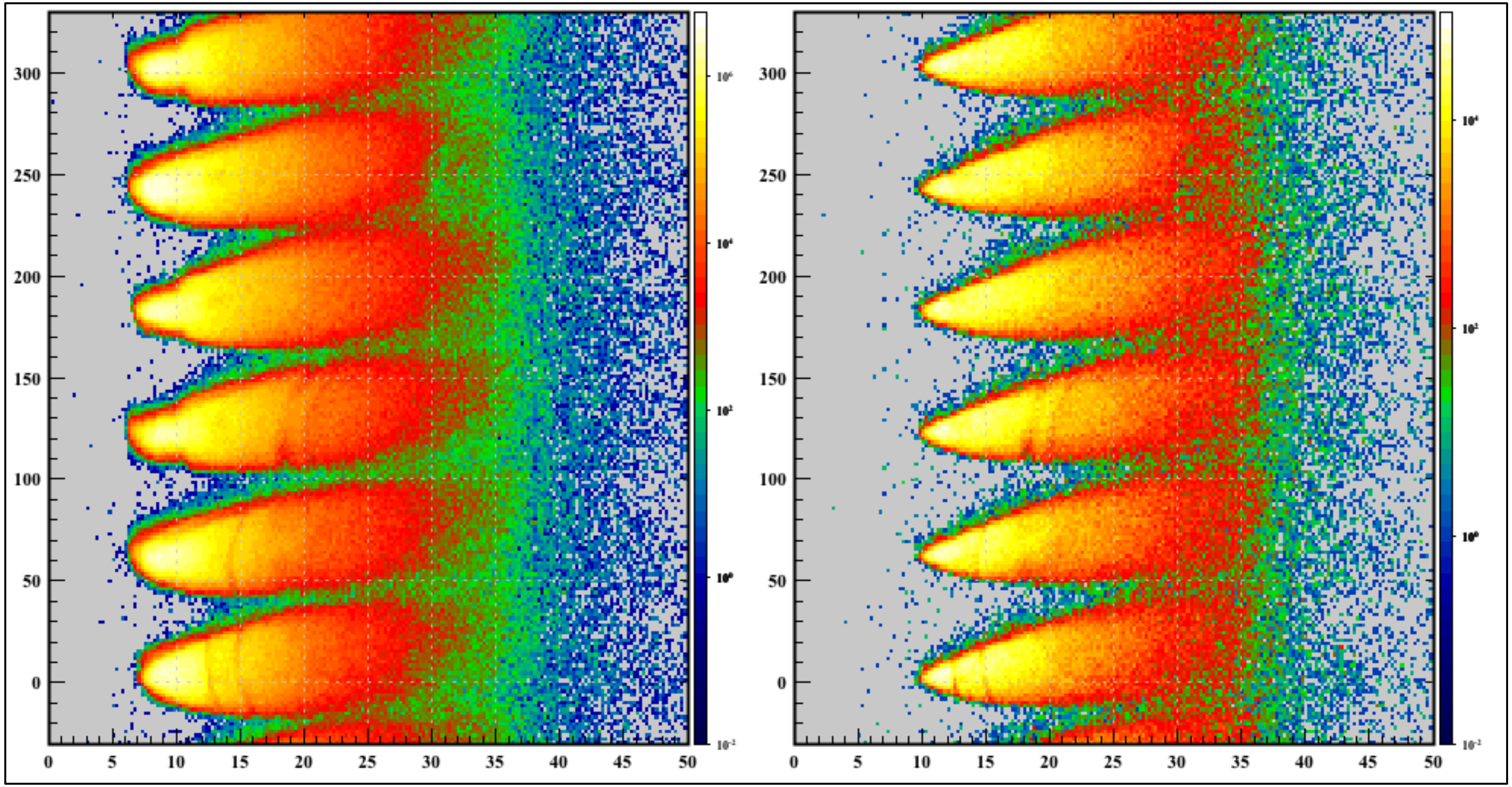
Dalitz plot





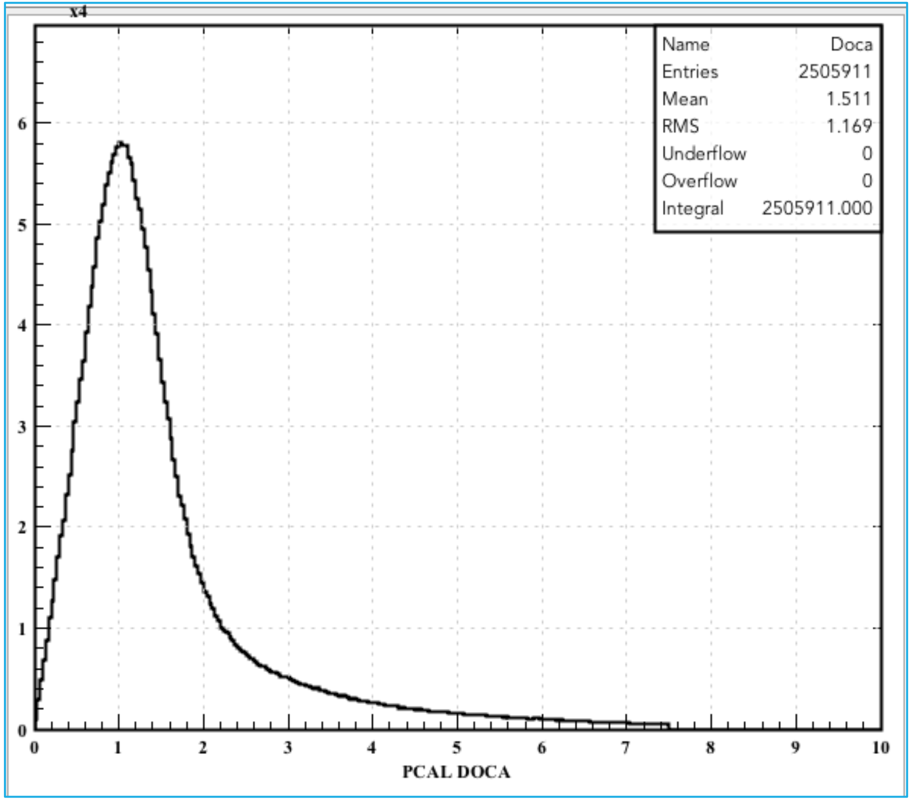
RG-A Analysis

ECAL $\phi(deg)$ vs $\theta(deg)$ distribution for negative particles before and after applying
PCAL U > 30 , 30< V < 390 , 30 <W <390 and chi2_calc(PCAL)< 2.0



RG-A Analysis

PCAL DOCA



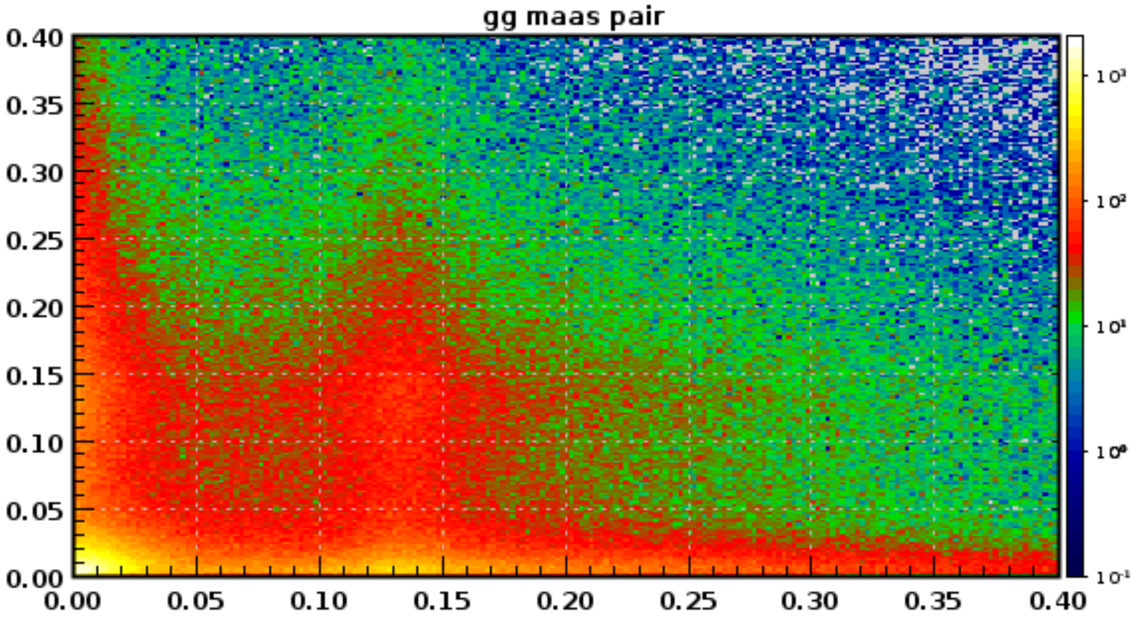
Doca Calculation

Doca=

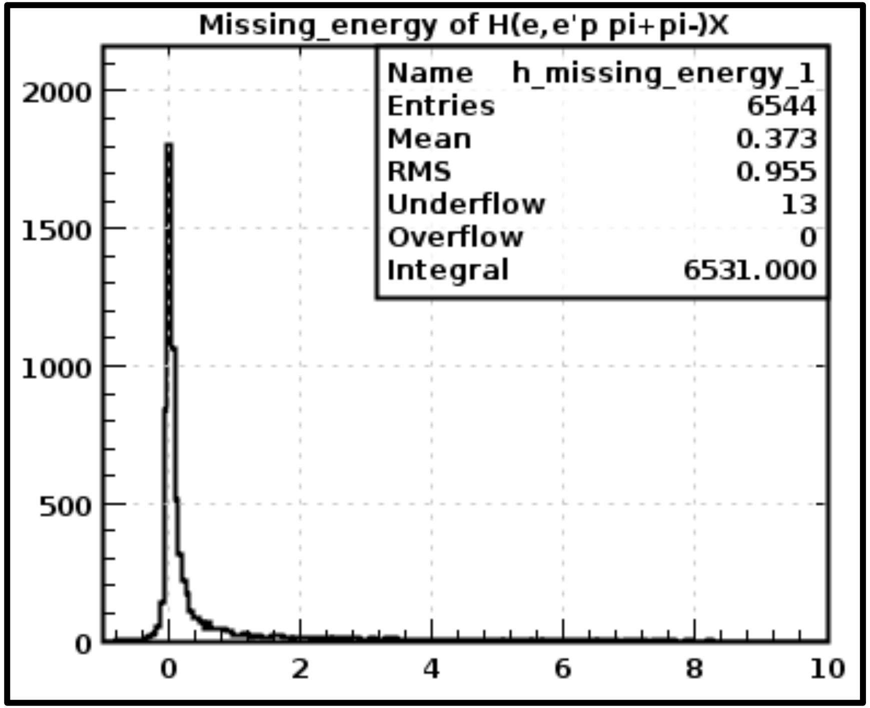
$$\sqrt{(x-hx)^2+(y-hy)^2+(z-hz)^2}$$

x - X coordinate of the hit (cm)
y - Y coordinate of the hit (cm)
z - Z coordinate of the hit (cm)
hx - X coordinate of the matched hit (cm)
hy - Y coordinate of the matched hit (cm)
hz - Z coordinate of the matched hit (cm)

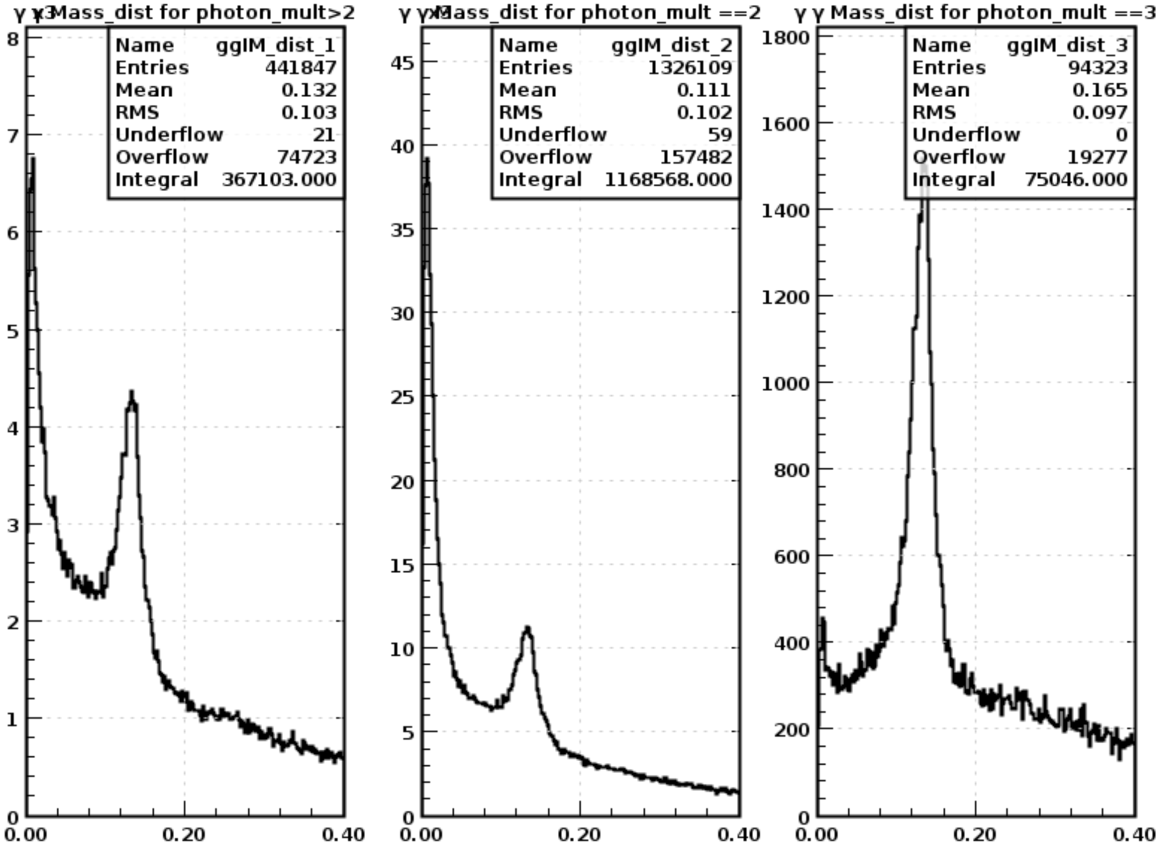
RG-A Analysis

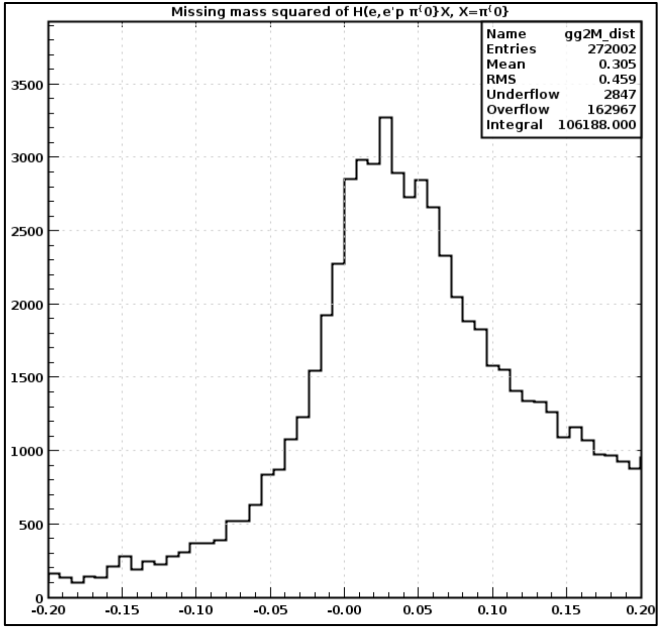


RG-A Simulation



RG-A Simulation

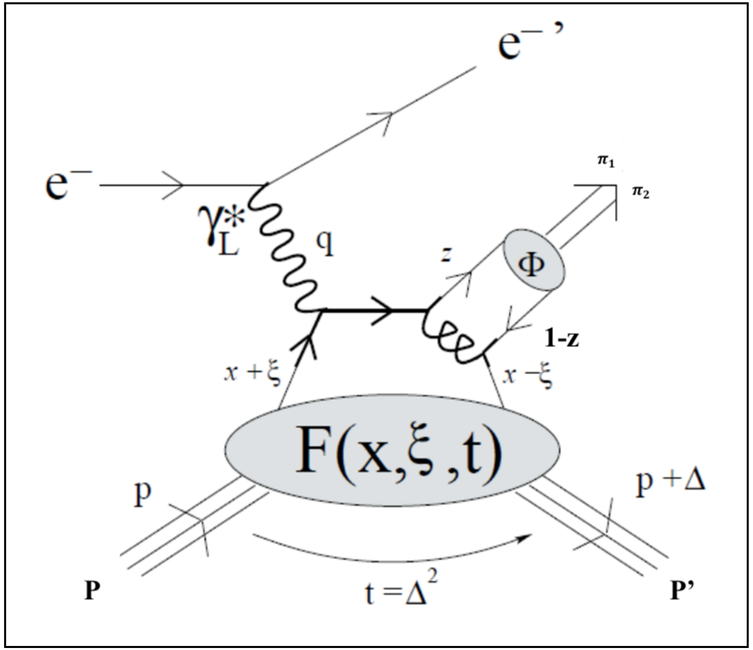




Zoom in

Deep exclusive two pion production

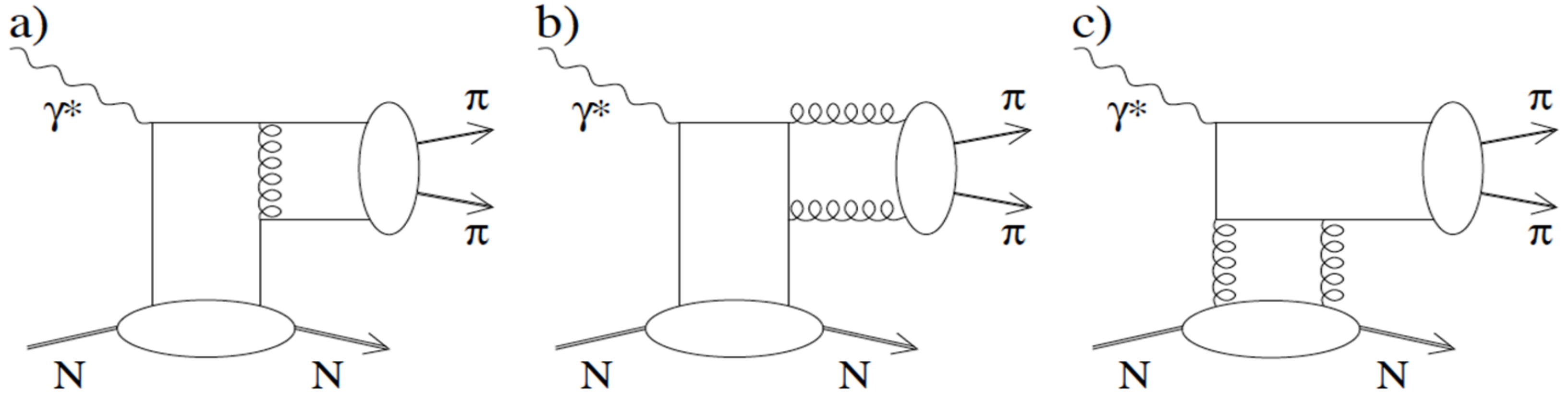
- Exclusive two-pion electroproduction
  - $e + p \rightarrow e' + p' + \pi_1 + \pi_2$



- In the one-photon exchange approximation we can reduce our analysis to the hadronic sub process.
  - $\gamma^* + p \rightarrow \pi_1 + \pi_2 + p'$

Deep Virtual Factorization

- Leading order diagrams for exclusive deep virtual production of two pions



B. Lehmann-Dronke et al., Phys Lett B 475 (2000) 147

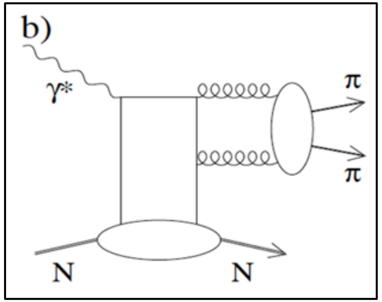
B. Lehmann-Dronke et al., Phys Rev D, 63 (2001) 114001

Neutral mesonic final state: $\pi^+\pi^-$ or $\pi^0\pi^0$

a) [Flavor-Diagonal quark-GPD] $\otimes$[$q\bar{q}$ -Two-Pion Distribution Amplitude (DA)]
b) [Flavor-Diagonal quark-GPD] $\otimes$[gluon-Two-Pion Distribution Amplitude(DA)]
c) [Gluon-GPD] $\otimes$[$q\bar{q}$ -Two-Pion Distribution Amplitude (DA)]

Deep Sigma

- σ-meson Asymptotic Distribution Amplitudes:
  - $\boldsymbol{\phi}_{gluon} = 2\,\boldsymbol{\phi}_{qq}$



- σ-meson: $f_0(500)$ well established.
  - Pole = (450±20)MeV – i(275±12) MeV) (J.R.Peláez)
- Microscopic structure of $f_0(500)$ not well understood.
  - $q\bar{q}$: $^3P_0$
  - Tetraquark
  - ππ -molecule
  - Glueball
  - Superposition of all of the above
- Deep sigma-production offers intriguing probe of gluonic content of $f_0(500)$.

Deep virtual $\pi\pi$ Production Amplitude

- **Deep Virtual $\pi\pi$ Production Amplitude**

$$\mathscr{M} = \sum_{\substack{J^\pi : I \\ \lambda_N, \lambda_\pi \in (q\bar{q}, g)}} \int d\tau dz \mathrm{GPD}_{\lambda_N}(\tau, \xi, t) \odot S_{\lambda_N, \lambda_\pi}(\tau, z, \xi) \odot \mathrm{DA}^I_{\lambda_\pi}(z, \zeta) P_J(\cos(\theta^*) \Omega_{J:I}(m_{\pi\pi})$$

- **Kinematics**

$$\xi \sim \frac{x_B}{2 - x_B}$$

$$t = (q - p_{\pi\pi})^2 = (P'_p - P_p)^2$$

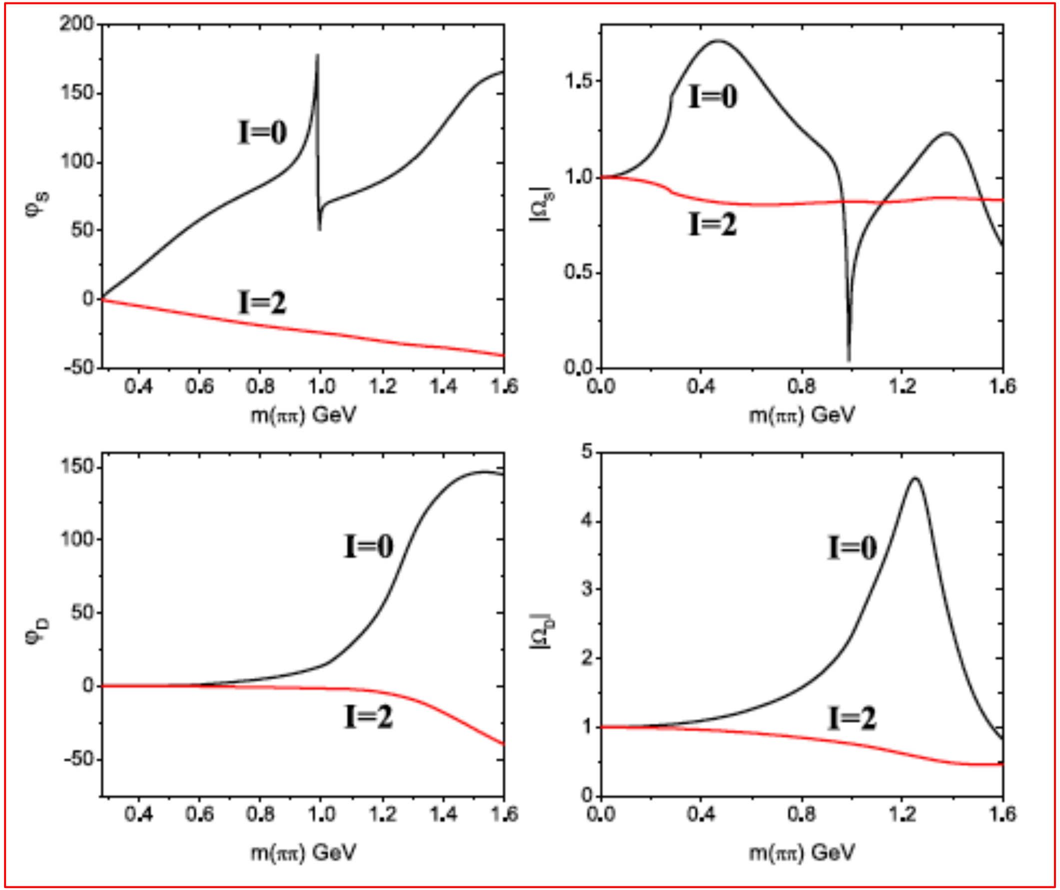
$$\zeta, (1-\zeta) = \frac{1}{2}[1 \pm \beta^* \cos\theta^*] = \text{ pion lightcone momentum fractions}$$

$$\beta^* = \text{ pion velocity in } \pi\pi \text{ rest frame}$$

$$\theta^* = \text{ pion polar angle in } \pi\pi \text{ rest frame}$$

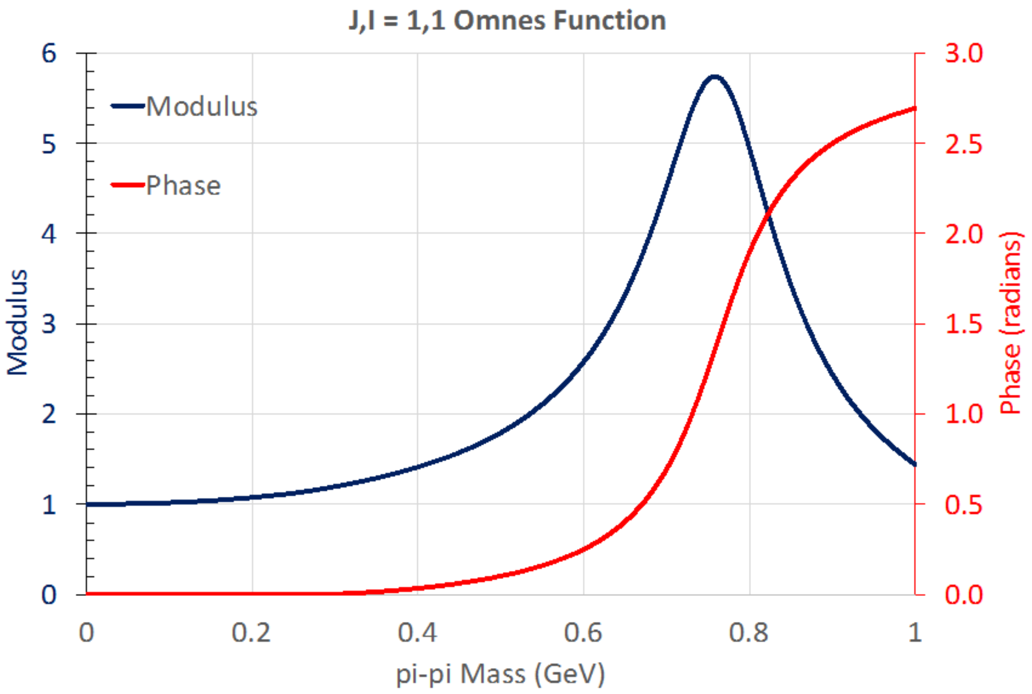
- **Dynamics**
  - S(τ,z;ξ) = Hard scattering amplitude (quark-gluon propagators)
  - $\Omega_{J;I}$ = Omnès-function, derived from ππ phase shifts
  - τ = average momentum fraction of parton in nucleon
  - z = momentum fraction of parton in ππ DA

$\pi\pi$ Mass Distribution (Omnès F'n)



- L.Dai, M.Pennington, Phys Rev D **90** 036004 (2014)
- $L = 0$
  - *f_0(500)*
  - *f_0(980)*
  - *Small I=2 non-resonant*
- $L = 2$
  - $f_2(1270)$
  - *Small I=2 non-resonant*

$\pi\pi$ Omnès F'n I;J = 1;1 (ρ-meson)



- L.Dai, M.Pennington, Phys Rev D **90** 036004 (2014)

$$\Omega_l^I(m_{\pi\pi}) = \exp\left\{ i\delta_l^I(m_{\pi\pi}) + \frac{m_{\pi\pi}^2}{\pi}\Re\left[\int_{4m_\pi^2}^{\infty} ds \frac{\delta_l^I(s)}{s(s-m_{\pi\pi}^2 - i\epsilon)}\right]\right\}$$

RG-A Analysis

Invariant mass distribution for$(\pi^+ + \pi^-)$
After applying following cuts

$M(\pi^+ + \pi^-) > 0.2$ GeV
$Q^2 > 1.0$ GeV^2
W > 2.0 GeV

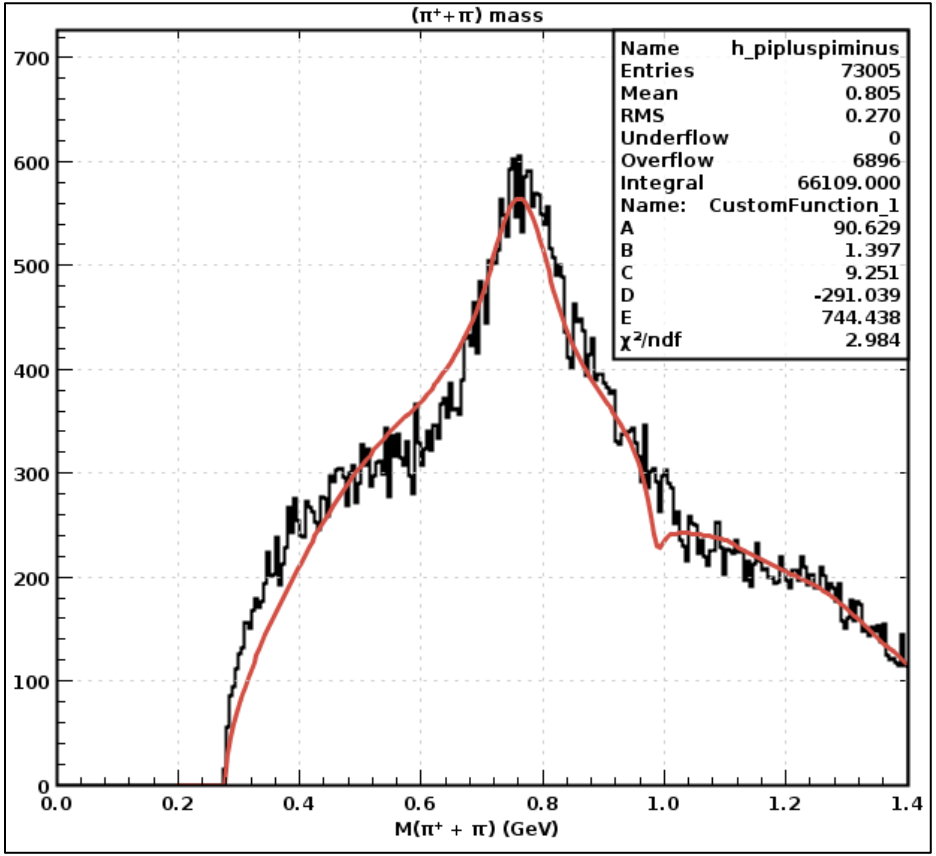
Missing Energy

$H(e, e'p\,\pi^+\pi^-)X > -0.5$ and
$H(e, e'p\,\pi^+\pi^-)X < 1.5$

Missing Mass

$H(e, e'p\,\pi^+\pi^-)X > -0.1$ and
$H(e, e'p\,\pi^+\pi^-)X < 0.1$

$$Ftting\ Function = (A|Omnes00|^2 + B|Omnes20|^2 + C|Omnes11|^2 + D|Omnes02|^2 + E|Omnes22|^2) * \sqrt{M_{\pi\pi}{}^2 - m_\pi{}^2}$$



RG-A Analysis

Identifying Pions

π^- - not an electron

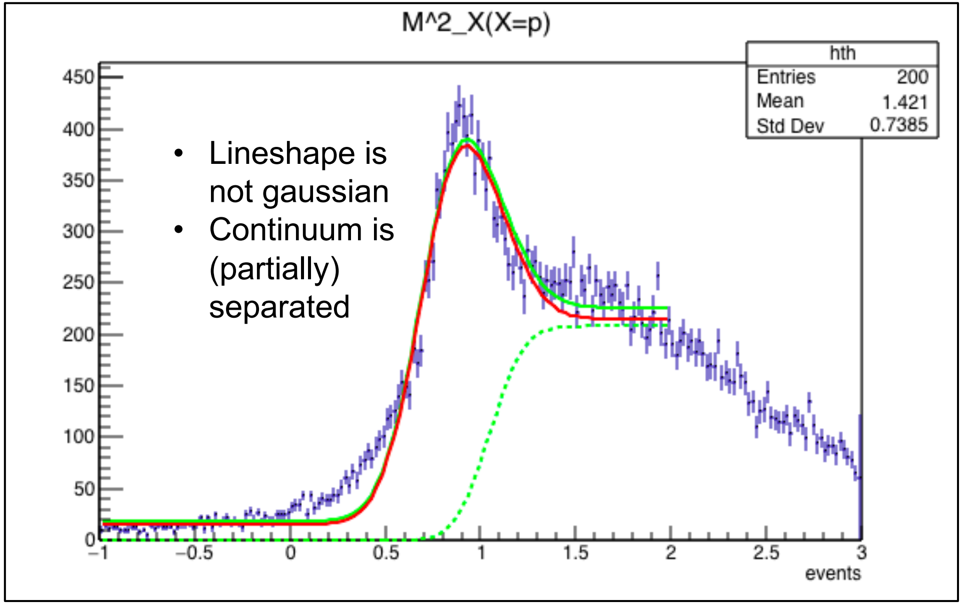
$\boldsymbol{\beta} > \boldsymbol{\beta}_3(p)$: $\boldsymbol{\beta}_3(p) = (1/2)(\boldsymbol{\beta}(\text{pion})(p) + \boldsymbol{\beta}(\text{kaon})(p))$

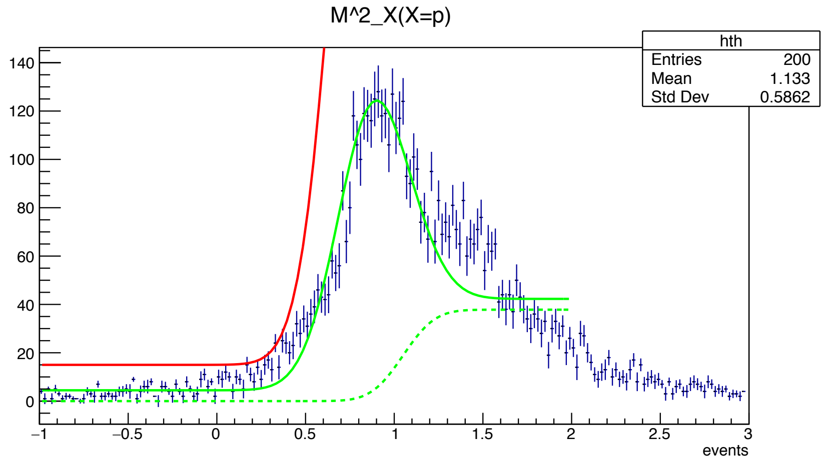
π^+ - $\boldsymbol{\beta} > \boldsymbol{\beta}_3(p)$

Delete this slide.
This pi- cut will remove half of your pions at large momentum,
Because tof resolution cannot separate beta(pion) and beta(kaon).

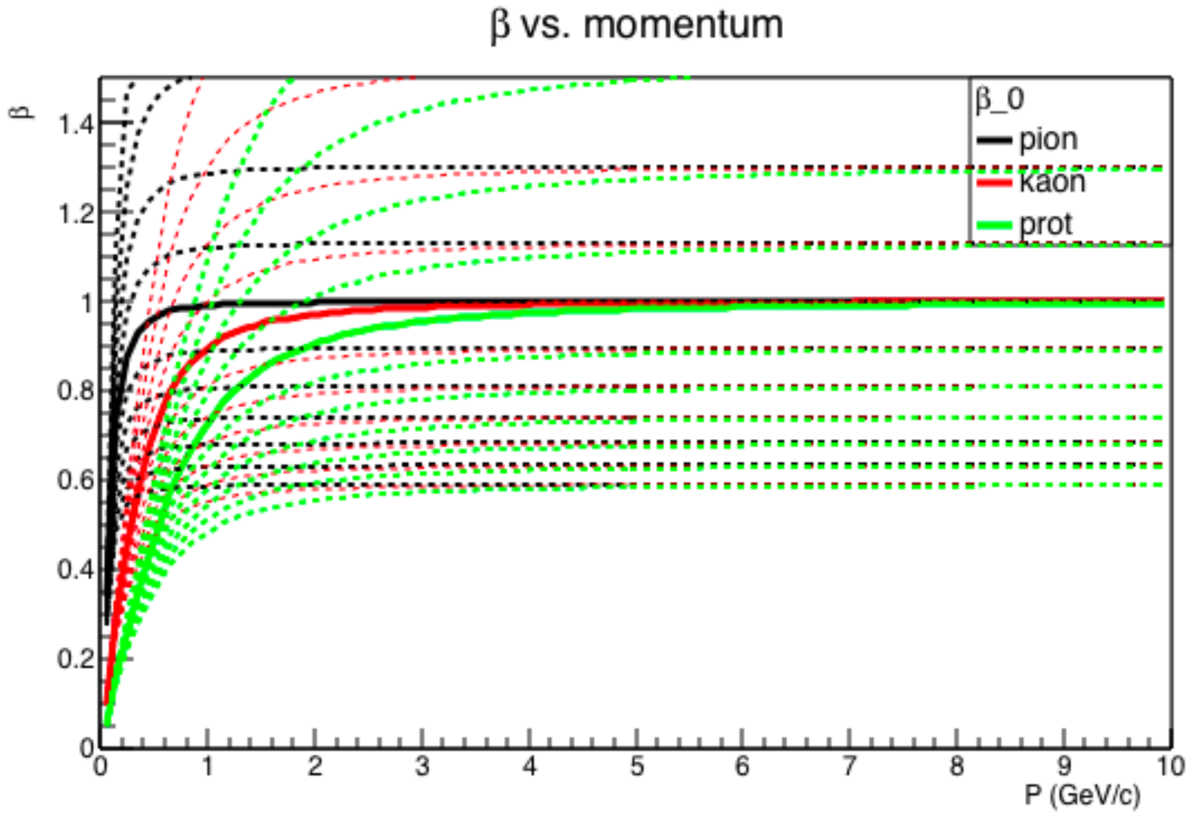
RG-A Analysis

Identifying Protons





RG-A Analysis



Dr. Hyde’s Plot

RG-A Analysis

- Isospin is a quantum number related to the strong interaction. It is mathematically similar to spin and it has nothing to do with angular momentum.

Iso-Spin

It was discovered that particles with approximately the same mass, and the same (ordinary) spin existed in “charge multiplets”:

p and **n** ➔ I_3 = ½, - ½ (a doublet)

π^+ π^- π^0 ➔ I_3 = 1, -1, 0 (a triplet)

number of states = 2I +1